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High Efficiency Fossil Power Plants (HEFPP) Conceptualization Program

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EXECUTIVE SUMMARY

This is the Final Report covering Energy Research Corporation's High Efficiency Fossil Power Plants (HEFPP) Conceptualization Program. The project was a cost-shared effort supported by the US Department of Energy through the Federal Energy Technology Center, Morgantown WV, under PRDA DE-RA26-97FT34164.

Under this project, Energy Research Corporation (ERC) has developed a fuel cell / turbine system that integrates the highly efficient baseline atmospheric pressure direct fuel cell with an unfired Brayton cycle running on the fuel cell waste heat. System analyses have been done using performance projections based on the baseline commercial product assumptions, which are reviewed annually in DOE's due diligence studies. Based on these performance assumptions, an efficiency of about 71% has been projected, with 85% of the power coming from the fuel cell section and the balance from the turbine section. System calculations have also been done with more aggressive fuel cell performance assumptions which indicate that LHV efficiencies close to 80% are possible in the longer term.

ERC has been evaluating plant designs which combine the carbonate direct fuel cell (DFC) with combustion and/or steam turbine generation equipment since early studies were done under a CRADA with FETC. The baseline hybrid system developed in the earlier studies involved the transfer of waste heat into a fired Brayton cycle through a very high temperature (2000 °F) heat exchanger. Under the HEFPP program, an alternate system has been developed which incorporates a number of improvements:

- The heat exchange temperature has been reduced to less than 1600°F, which is in the range of commonly available high temperature heat exchange materials.
- The Brayton cycle is an unfired system, indirectly heated with fuel cell waste heat. This yields the highest efficiency, since all primary fuel consumption is done in the fuel cell - which is the more efficient portion of the system.
- Cathode gas and anode gas recycle blowers have been eliminated. All gas supply is accomplished with the normal natural gas pressure and the air compressor associated with the turbine equipment.
- High efficiency is obtained without the use of an additional steam bottoming cycle, eliminating the need for high pressure boilers (a concern with respect to unattended operation).

In addition to these improvements over our previous hybrid system, the system also retains these features of the DFC hybrid:

- Two key features of our baseline simple cycle DFC product are retained: Ambient pressure operation and internal reforming. This is the most efficient and reliable

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configuration of the fuel cell section of the power plant. It also avoids the need for a high pressure boiler to provide steam for the fuel cells.

- The system allows the turbine pressure ratio to be set independently of fuel cell pressure considerations.
- Although in normal hybrid operation the turbine will be unfired, a burner could be provided in the turbine to allow independent operation of the turbine, replacing the existing fuel cell startup burner. Conceptually, the turbine section could be producing power during the fuel cell startup.
- The turbine section can be used to load follow - utilizing stored kinetic energy - while the fuel cell is efficiently baseloaded at constant power. This is only possible because of the decoupled nature of the fuel cell and turbine sections of the plant.

Figure ES-1
Simplified Diagram of Selected Hybrid Design

Figure ES-1 shows a simplified system diagram for the hybrid system developed in the project. The system concept is as follows. Fuel and water are sent to the system Heat Recovery Steam Generation (HRSG) unit, where steam is produced and mixed with heated fuel for use as the DFC fuel gas feed. The DFC - which produces 17 MW - operates at 78% fuel utilization, and residual fuel from the anode exit is consumed in an anode exhaust oxidizer. Air is compressed in an intercooled compressor to about 16 atm, heated with system exhaust in the HRSG, heated further with exhaust from the anode exhaust oxidizer, and expanded in a turbine. The turbine produces about 3.4MW net power output. The expanded, low pressure air leaving the turbine is used

as the oxidant in the anode exhaust oxidizer. Flue gas leaving the oxidizer is first cooled by the turbine air, and then sent as the cathode feed gas to the fuel cells. The cathode exhaust gas is sent through the HRSG to provide the required pre-heat and water vaporization.

The following operating characteristics are projected for the hybrid system:

Fuel Cell:

DC Power: 17.62 MW
AC Power, Gross: 17.00 MW

Turbine

Compressor Power: 5.84 MW
Expander Output: 9.28 MW
Net Output: 3.44 MW

Parasitic 0.03 MW

Total Plant Output: 20.41 MW

Overall LHV Efficiency: 71.08%

In addition to development and optimization of the process design, the project also included the development of an optimization tool, consisting of an EXCEL^(TM) based spreadsheet model of the system. The basic system design of the selected hybrid plant was developed with ChemCAD^(TM) process modeling software, which was augmented with an ERC-developed fuel cell add-in model. This approach was used to select the optimum flowsheet. Once this was done, a model of the selected system was built in Microsoft EXCEL^(TM). This model is being submitted along with the final report. It allows the user to vary key system parameters to assess the impact on system performance, and provides a more in-depth understanding of the design.

Once a system design was selected from among the process options, work was done to specify the power plant equipment items. This was done using both the ChemCAD^(TM) model and the EXCEL^(TM) spreadsheets, and both tools were found to agree very closely. Once equipment specifications and sizes were established, a preliminary layout of the powerplant was developed. This is shown in Figure ES-2.

Figure ES-2
Preliminary Layout of 20MW Hybrid Powerplant

A cost estimate was developed for the powerplant, using assumptions specified by FETC in the September 24, 1998 "Reporting Requirements". An installed equipment cost of \$17,520,242, or \$858/kW is projected. Cost of energy calculations were done, also using economic assumptions specified in the FETC Reporting Requirements. As shown in Figure ES-3, the system was found to be cost competitive with conventional combined cycle equipment for cases where natural gas cost was \$2/MMBtu or greater.

The cost estimate was also evaluated in a Risk Assessment task, in which probabilistic curves were assigned to individual cost estimate line items, and the impact on projected system cost was assessed. Crystal Ball ^(TM) software was used for this analysis. This software is a Microsoft EXCEL ^(TM) add-in which runs over the spreadsheet-based cost estimate and uses a Monte-Carlo simulation to evaluate the overall probability of meeting or exceeding the projected cost. The simulation projected an 80.8% probability that the system cost would be equal to or lower than the overall estimated cost.

Figure ES-3: Cost of Energy Comparison with Gas Turbine Cycle

Figure ES-4: Risk Analysis Probability Distribution for Powerplant Cost

ERC was assisted in the program by Allison Engine Company, who provided valuable insight into the turbine design issues. Along with providing design and cost details to support the selected system design (which utilizes a specialized turbine with intercooled compressors and a reheat expansion cycle), Allison personnel also noted that the design concept could be used with more conventional turbomachinery. Near term plants could be configured with available machinery from their existing product lines and achieve LHV efficiencies in the mid 60 percent range.

In summary, the HEFPP project has identified an attractive DFC/Turbine hybrid design which offers the promise of very high efficiency in a relatively simple system. Additional work which was out of the scope of the study and which needs to be done on the design includes:

- Analysis of performance issues at partload
- Startup, shutdown, and control issues
- Evaluation of possible independent operation of turbine, e.g. during fuel cell heatup
- Evaluation of near-term options for proof-of-concept, field trials, and early market entry, including:
 - Smaller systems. Hybrids based on ERC's market entry sub-MW, 1.5 MW and 3 MW power plants could offer very high efficiencies at their respective size levels
 - Field test powerplants, consisting of hybrids with ERC's 200kW, 1MW, or 2MW near term field test systems
- Detailed design of system-specific components. An advantage of the selected system is that there are no long term developmental issues in the balance of plant (like the high temperature heat exchanger from the earlier system). Certain components are unique to the hybrid system, and will require additional design specification. Examples include the anode exhaust oxidizer (which operates at a higher temperature than the one in the baseline simple cycle system) and the multi-stage turbomachinery.

With these activities as a next logical step, a path forward is possible which can lead to the availability of very high efficiency power plants in the near future.

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1.0 INTRODUCTION

1.1 Technology Background and Earlier Hybrid Work

This is the Final Report covering Energy Research Corporation's High Efficiency Fossil Power Plants (HEFPP) Conceptualization Program. The project was a cost-shared effort supported by the US Department of Energy through the Federal Energy Technology Center, Morgantown WV, under PRDA DE-RA26-97FT34164.

Energy Research Corporation (ERC) began working on the carbonate fuel cell in the mid-seventies, and is currently recognized as the technology leader. An advanced version of the carbonate fuel cell system has been developed at ERC in which the necessary reforming reactions occur within the fuel cell stacks, eliminating the need for a reforming subsystem in the power plant. This version of the carbonate technology - the Direct Fuel Cell (DFC) - is characterized by extreme simplicity, which contributes to the system's inherently low cost and high reliability. In an extension of this philosophy of system simplification, ERC's system operates at ambient pressure, and is configured with only one prime mover, a cold air blower. The system concept is shown in Figure 1.1.

Figure 1.1
Baseline Simple Cycle System Design

The process involves treating natural gas to remove impurities, after which it is mixed with steam and sent to the fuel cell stacks. The fuel/steam mixture is reformed in the stacks, providing the hydrogen which is consumed in the fuel cell anodes (at a hydrogen utilization of up to 80%). The anode reaction also produces CO_2 , which is required in the fuel cell cathodes. The cathode feed is produced by taking the anode exhaust, catalytically reacting any residual fuel with air, and sending the flue gas with excess air to the cathodes. Cathode exit gases are sent to a packaged heat recovery unit to supply heat for steam generation, fuel pre-heat, and final heating of the steam/fuel anode feed gas.

This DFC power plant system has several attractive features. The system operates at ambient pressure, which has been shown in studies conducted by ERC and Fluor Daniel, Inc. (FDI) to have a beneficial impact on cost of energy. Compared to operation at higher pressures, the atmospheric pressure design utilizes lower cost components and exhibits longer fuel cell stack life. Potential customers of these power plants have indicated that the system will be acceptable in a wider range of applications if it is not pressurized. Also, operation of the system at atmospheric pressure limits the pressure differentials which can be imposed on the fuel cell stacks in the event of a plant upset. Another aspect of atmospheric pressure operation is that it facilitates the use of internal reforming, which is inhibited at higher operating pressures.

The internal reforming feature of ERC's Direct Fuel Cell Power plant has many advantages. The obvious cost savings associated with the elimination of a large fired external reformer is one of the principle advantages. Internal reforming also enhances system efficiency, since the reforming reaction helps to remove stack waste heat, eliminating the need to increase the cathode gas flow (with a substantial increase in parasitic power) to remove heat. Heat removal via cathode gas alone usually also requires a cathode gas recycle system, which adds to system cost and complexity. An additional efficiency gain occurs because internal reforming can be done at low steam to carbon ratios (since consumption of reactant in the anodes drives the reforming equilibrium to completion), which improves the performance of the fuel cell anodes.

The system concept has been tested at the multi-megawatt level in ERC's 2MW Santa Clara Demonstration Project (SCDP), a cost-shared DOE Cooperative Agreement program which demonstrated the advantages of the system concept. The strengths of the atmospheric pressure, internal reforming, Simplified Design were demonstrated by the robust performance of the balance of plant (BOP). Over the 4000 grid-connected hours of operation, the BOP exhibited an availability of 98% (99% if operator procedural errors are discounted).

Given the attractive features of the atmospheric pressure, internally reformed, DFC concept, both in principle and as demonstrated at the 2MW level in Santa Clara, the use of the system as the basis for an ultra high efficiency power plant is a logical step. In addition to the baseline simple cycle design, this project had as another starting point a baseline hybrid system, which had been developed earlier by ERC under a ERC/FETC Crada which evaluated hybrid systems ranging from 20 to 200MW in size. The system design used in the 200MW system (scaled down to 20MW), was selected as a baseline for the current program, since it exhibited efficiency above 70%.

A flow diagram of this first generation hybrid power plant is shown in Figure 1.2. In this system, about 95% of the fuel was sent to the fuel cell stacks, where the fuel was reformed and consumed at 80% utilization. Five percent of the fuel was compressed and sent to the gas turbine combustor. The gas turbine compressor delivered air at 360 psia to a high temperature heat exchanger which heated the air to 982°C (1800°F). The heated air then flowed to the gas turbine combustor where it was heated further to 1094°C (2000°F) before flowing through the turbine. Turbine exhaust was split, with 50% of the stream flowing to the fuel cell cathodes and 50% flowing to the anode exhaust burner. Exhaust from the anode exhaust burner heated 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 (1250°F) went to a steam bottoming system. Exhaust from the cathodes at 677°C (1250°F) went to a steam bottoming system.

Figure 1.2
First Generation Hybrid Design System

The projected performance of this system at the 20 MW level is summarized in Table 1.1.

Table 1.1
Power Output Summary from First Generation 20 MW hybrid system

Direct Fuel Cell Power	15.7 MW
Gas Turbine Power	2.8 MW
Steam Bottoming Cycle	2.9 MW

Total Power Output, Gross DC	21.4 MW
Parasitic Power	0.8 MW

Net Power Output, Net AC	20.6 MW

This system has a high projected efficiency (72.5% LHV), preserves the basic features of the DFC design (atmospheric pressure, internal reforming), and provides a degree of independence between the fuel cell and turbine systems. However the system is substantially more complex than the baseline simple cycle system. Anode and cathode recycle streams have been added, and the system requires a steam turbine bottoming cycle to achieve >70% efficiency. In addition, it requires a heat exchanger which operates at 2000°F. Addressing these concerns was a major objective of the current HEFPP program.

1.2 HEFPP Project Description

The overall objective of the program was the development of a conceptual design of a cost effective, environmentally friendly, power plant which operates with an LHV fuel efficiency on natural gas of 70% or better. It was important that the high efficiency system be configured with technologies which will exhibit the high reliability and availability demanded by power applications, and which can be commercialized in the first decade of the next century. An additional objective of the program was the identification of the required path forward for development and commercialization of the system.

To provide a baseline for optimization efforts and cost analyses, FETC prepared a "Reporting Requirements" document which was reviewed by HEFPP contractors and finalized in a September 24, 1998 issue. The design and cost assumptions established in the Reporting Requirements document are summarized in Table 1.2.

Table 1.2
Summary of FETC Reporting Requirements Assumptions

<ul style="list-style-type: none"> • Systems should be sufficiently developed in time for demonstration in the year 2010 or sooner • Application is Commercial distributed-power generation utility - grid connected. 	
Fuel:	Natural gas, Composition: CH ₄ , .96; N ₂ , .02; CO ₂ , .02; S, 4 ppmv. mercaptans
Fuel supply pressure	15 psig
Fuel supply temperature	59°F
Air composition:	Oxygen, .207; Nitrogen, .78; CO ₂ , .003; Water, .01 (60% relative humidity)
Ambient air temperature	59°F
Ambient air pressure	14.7 psia
Ambient Air Parameter Ranges	
Pressure	Sea level to 5000 ft.
Temperature	-20°F to 120°F
Relative Humidity	0 to 100%
Performance Requirements	
Design-Point Capacity	20 MW net AC, +/-2 MW
Design-Point Efficiency	> 70% (net AC/LHV)
Power System Dispatch Mode	Base loaded
Turndown Requirement	None
Overpower Requirement	None
Output Power Conditions	60 Hz
	Utility-grid quality
Noise Control	Consistent with typical gas turbine power plant practice
Power System Physical Design Objectives	
Installation	Outdoors
Transportation Options	Truck, sea, air, rail
Transportation Basis	500 miles
Plant Design Lifetime	Conventional power plant equipment - 25 years
Utilities	All utilities needed to support the plant will be available
Power Plant Operation	
Annual Operating Time	Fifty weeks
Annual Planned Shutdown	Two weeks
Instrumentation and Control	The I&C system design concept and cost will be based on the projected needs of mature fuel cell/gas turbine technologies and commercial power plant operation.
Economic Evaluation Parameters	
Power System Cost Estimation Basis	Mature technologies & integration techniques, not first-of-a kind.
Cost Basis	Mid-1998 US dollars
Fuel Cost	\$3.00/MMBtu (HHV)
Capital Charge Rate	15%
Capacity Factor	92%
COE Evaluation Method	Constant dollars
Power Plant Optimization Basis:	Consistent with >70% (LHV) efficiency, achieve a design-point COE that is 10-20% below the COE achieved by today's conventional-plant technology.
Basis for COE Comparison:	Comparably sized gas turbine cycle

In addition to the cost analysis basis positions established in the Reporting Requirements document, ERC's HEFPP project SOW called for additional specific costs sensitivity analyses and risk analysis, along with the development of the system design, cost estimate, and spreadsheet model. These project results for these activities are described in the following sections.

2.0 PROJECT RESULTS

The tasks in the program were as follows:

Task 1: Conceptual Electronic Systems Model, which involved the development of the system design, and the generation of a spreadsheet based model of the system.

Task 2: Equipment Sizing and Specification, based on the chosen system.

Task 3: Cost Estimating, based on the equipment sizing.

Task 4: Financial Analysis and Risk Analysis, which included cost of energy estimation, and evaluation of the sensitivity of the COE to fuel cost.

The project was initiated in June, 1998 and ran through March, 1999. Results of the task activities are described below.

2.1 Task 1: Conceptual Electronic Systems Model

2.1.1 Process Development

As noted above, at the start of the project, a hybrid baseline was in place based on the earlier CRADA work. The process development work in the HEFPP project had the objective of identifying a more simple hybrid design. Areas which were examined included advanced "stretch-goal" fuel cell concepts as well as improved hybrid system ideas. Initial studies were conducted in the following areas:

- Advanced Fuel Cell Concepts, projecting substantially higher fuel utilization or operating voltages than are currently obtainable.
- Advanced Fuel Cell Configurations, for example fuel cell networks, in which fuel cell stacks are bottomed by other fuel cell stacks. In this approach the residual fuel from one set of stacks can be sent to a second string of stacks for additional utilization.
- Improved hybrid systems, with the objective of identifying simpler designs, with fewer developmental components than the baseline.

When the FETC Reporting Requirements document was issued in September it stated that "system performance parameters used in these calculations should either be currently obtainable or any extrapolations should be justified." With this direction, it was

determined that the appropriate fuel cell performance assumptions used in the project should be the projections used in our baseline commercial plant design. This design is reviewed annually in DOE's due diligence effort. The fuel cell performance assumed in the design has been demonstrated in small cells and the technology effort required to achieve it in full size stacks is in place in ERC's DOE-supported Product Development and Improvement (PDI) program. ERC has other ongoing projects which are developing cell designs with higher performance levels, but these are longer term activities.

Given this direction, it was decided to pursue the advanced stack and stack configuration concepts only for comparison purposes. The advanced stack concept clearly looks to long term performance levels beyond the scope defined in the Reporting Requirements. To some extent the advanced stack configuration approach also needs longer term stretch goals to be feasible. The concept is equivalent to developing a stack technology which can operate at very high fuel utilizations. One drawback is that the capital cost and replacement cost of the additional stacks can become prohibitive unless stack life can be extended, or unless stacks can be developed which can operate efficiently on very dilute fuel. Both approaches should be considered in longer term studies, but were out of the scope of the current work.

The work therefore focused on evaluation of alternate hybrid systems which eliminated some of the complexity and developmental components from the baseline design. The first system evaluated was an alternate hybrid system in which residual fuel in the anode exhaust was utilized directly by combustion in the Brayton cycle. This eliminated the high temperature heat exchanger in the baseline hybrid system. Various system options were implemented and simulation runs were performed. While the system did eliminate the high temperature heat exchanger, it had issues which led to its rejection. The principle problem with the system was additional system complexity associated with cooling and drying the anode exhaust before compression.

The hybrid system which was evaluated next involved a return to the approach of indirectly transferring sensible heat to the turbine cycle. By refining the heat exchange approach used for this transfer, the temperature of the heat exchange equipment was reduced from the 2000°F in the baseline design to a more practical 1600°F. It was also decided to eliminate supplemental firing of fuel in the turbine cycle, the principle being that since the fuel cell is the most efficient conversion device in the system, all fuel should be sent to it. The development of this system then boiled down to extracting heat as efficiently as possible from our baseline fuel cell system.

The system design which resulted from these efforts is shown schematically in Figure 2.1. The system concept is as follows. Fuel and water are sent to the system Heat Recovery Steam Generation (HRSG) unit, where steam is produced and mixed with

heated fuel for use as the fuel cell gas feed. The fuel cells - which produce 17 MW - operate at 78% fuel utilization, and residual fuel from the anode exit is consumed in an anode exhaust oxidizer. Air is compressed in an intercooled compressor to about 16 atm, heated with system exhaust in the HRSG, heated further with exhaust from the anode exhaust oxidizer, and expanded in a turbine. The turbine, which incorporates a reheat cycle, produces about 3.4MW net power output. The expanded, low pressure air leaving the turbine is used as the oxidant in the anode exhaust oxidizer. Flue gas leaving the oxidizer is first cooled by the turbine air, and then sent as the cathode feed gas to the fuel cells. The cathode exhaust gas is sent through the HRSG to provide the required pre-heat and water vaporization.

Figure 2.1
Simplified System Schematic of Selected Hybrid Design

Attractive features of this system include the following:

- The system meets the project goal of LHV efficiency above 70%.
- The heat exchange temperature has been reduced to less than 1600°F, which is in the range of commonly available high temperature heat exchange materials.
- The Brayton cycle is an unfired system, indirectly heated with fuel cell waste heat. This yields the highest efficiency, since all primary fuel consumption is done in the fuel cell - which is the more efficient portion of the system.
- Cathode gas and anode gas recycle blowers have been eliminated. All fuel and oxidant supply is accomplished with the 15 psig natural gas pressure and the air compressor associated with the turbine equipment.

- High efficiency is obtained without the use of an additional steam bottoming cycle, eliminating the need for high pressure boilers (a concern with respect to unattended operation).
- Two key features of our baseline simple cycle DFC product are retained: Ambient pressure operation and internal reforming. This is the most efficient and reliable configuration of the fuel cell section of the power plant. It also avoids the need for a high pressure boiler to provide fuel cell steam.
- The system allows the turbine pressure ratio to be set independently of fuel cell pressure considerations.
- Although in normal hybrid operation the turbine will be unfired, a burner could be provided in the turbine to allow independent operation of the turbine, replacing the existing fuel cell startup burner. Conceptually, the turbine section could be producing power during the fuel cell startup.
- In principle, the turbine section could be used to load follow - utilizing stored kinetic energy - while the fuel cell is efficiently operated at constant power. This is only possible because of the decoupled nature of the fuel cell and turbine sections of the plant.

Fully exploiting the last two items in the list will involve additional study, and was beyond the scope of this project, which was limited to baseload cases without turndown or overpower requirements.

During the development of this system, Allison Engine Company was consulted to provide overall review of the flowsheet concepts, and to provide detailed turbine design information. Allison provided the turbine specifications and costs which supported the Tasks 2 and 3 equipment sizing and costing efforts. They also helped refine the modeling effort in Task 1 by providing turbine and compressor efficiency data based on our preliminary model runs. They also offered the observation that while the selected system is attractive and meets the project goals, it requires turbomachinery with intercooled compressors and expander reheat which are not off-the-shelf items. No technological issues stand in the way, but the normal costs of new product development and retooling would have to be incurred. It was noted that if a system could be configured without compressor intercooling and expander reheat, it could be a good match with existing Allison equipment.

This was pursued to the point where system configurations were identified which did not meet the 70% efficiency objective, but which had efficiencies in the mid-60's and which could use existing turbomachinery from the 501K family. While the 70% system remained the project baseline, these lower efficiency alternates are worth investigating in future studies.

A summary of the results of the process development activities described above is presented in Table 2.1.

Table 2.1
Summary of System Designs Evaluated
The Bold Column is the Selected System Design

	1	2	3	4	5	6	7
	Simple Cycles			Hybrids with Intercooling & Reheat		Hybrids with Single Stage Compression & Expansion	
Fuel Cell Performance Assumptions							
Cell Voltage, mV	846	826	817	826	817	817	817
Fuel Utilization, %	94	94	78	94	78	78	78
Fuel Cell Section							
DC Power Out, MW	22.27	22.27	22.03	22.27	17.62	17.62	17.62
AC Power Out, Gross	21.75	21.75	21.52	21.49	17.00	17.00	17.00
Brayton Cycle							
Compressor Power				3.84	5.84	4.95	3.79
Expander				5.58	9.35	6.60	5.90
Power Net				1.73	3.51	1.65	2.11
Net AC Out				1.70	3.44	1.62	2.07
Parasitic	0.26	0.26	0.26	0.03	0.03	0.03	0.03
Net Power Output	21.49	21.49	21.26	23.16	20.41	18.59	19.04
Overall LHV Efficiency	74%	72%	58%	78%	71%	65%	66%

The first three columns are simple cycle (fuel cell only) systems, which represent various levels of fuel cell performance projection. The first two columns are aggressive projections, incorporating long term fuel cell technology advances or fuel cell network concepts. These studies indicated that within the bounds of what is thermodynamically possible, simple cycle or networked DFC's could achieve efficiencies in the mid-70's in the very long term.

Columns four and five are for the selected hybrid system. The first hybrid incorporates stretch-goal fuel cell projections, and achieves an efficiency close to 80%. It can be

seen that the turbomachinery does not contribute much additional power to the system, since there is so little waste heat left over from the very efficient fuel cell. The second hybrid incorporates our standard commercial plant projections. The system is projected to operate at 71.08% LHV efficiency at the rated power output point of 20.41 MW. This is the system which was carried forward into the EXCEL^(TM) model development and costing tasks described below.

The last two columns, 6 and 7, are for hybrid systems incorporating existing single stage turbomachinery at two pressure ratios. The column 6 case (with a pressure ratio of 9, and 36 lb/sec of turbine exhaust flow) is a good match for Allison's 501KB7 in unboosted configuration. While these systems do not meet the 70% LHV target efficiency, they may offer opportunities to field relatively efficient systems sooner than the 2010 time frame.

2.1.2 EXCEL^(TM) Model Development

The HEFPP project statement of work called for the development of a model of the system for electronic reporting purposes and enhanced sharing with the technical community. It was requested that commonly available computer spreadsheet software such as Microsoft EXCEL^(TM) be used for this purpose. Once the process was defined by the work with ChemCAD^(TM) modeling, work began on preparing the deliverable spreadsheet model.

The model establishes power output, efficiency, key process performance parameters, process flows, gas compositions, temperatures, pressures, and mass and energy balances throughout the power plant system. The model is programmed with certain power plant design assumptions which are presented as reference values. The sensitivity to each of the key reference design assumptions can be evaluated by an input parameter deviation. The model iterates the flows and energies in the system based on the parameter deviation until there is energy, atom and mass balance convergence throughout the system. The resulting impact on the power plant performance and conditions throughout the system is displayed.

A description of the model and a complete "user's manual" is included as Volume II of this Final Report. The model analysis at the Rated Power Output condition of 20.41 MW is summarized in Figure 2.2 and Table 2.2. Figure 2.2 shows the detailed system schematic, with heat and mass balance node numbers on relevant streams. The 3-page Table 2.2 summarizes the heat and mass balance for the plant, referring to node numbers on Figure 2.2.

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Figure 2.2
Detailed System Schematic with Node Numbers

Table 2.2: High Efficiency Power Plant Heat and Mass Balance Summary

INPUT PARAMETERS		FIXED REFERENCE	+/- DEVIATION	OUTPUT CHARACTERISTICS	
CH4 INPUT, MOLES/HR	=	296.00	0	NET AC POWER, KW	= 20,411
PROCESS AIR FLOW, MOLES/HR	=	4570	0	NET AC LHV EFFICIENCY, %	= 71.08
AMBIENT AIR TEMP F	=	59	0	PARASITIC LOSSES, KW	= 31
WATER VAPOR PRESS, PSIA	=	0.147	0	GROSS AC POWER	= 20442
FUEL LOWER HEATING VALUE, BTU/SCF	=	872.5	N/A	PLANT EXHAUST TEMP, F	= 208.6
CELL STACK				FUEL CELLS	
CELL VOLTAGE	=	0.817	0	FUEL CELL AC OUTPUT, KW	= 17002
CURRENT DENSITY, AMPS/CM ²	=	0.16	0	FUEL CELL DC POWER, KW	= 17619
NUMBER STACKS	=	48	N/A	FUEL UTILIZATION, %	= 78.0
NUMBER CELLS/STACK	=	360	N/A	CATHODE EXIT TEMP, DEG F	= 1173.6
CELL AREA, M ²	=	0.78	N/A	CATHODE INLET TEMP, DEG F	= 1035.8
ANODE EXIT TEMP DEG C	=	1170	0	FUEL CELL OXYGEN UTILIZATION, %	= 54.0
METHANE CONVERSION, %	=	100	N/A	FUEL CELL INLET O2 FRACTION	= 0.1236
STACK HEAT LOSS, MBTU/HR	=	700,000	0	OUTLET O2 FRACTION	= 0.0711
INVERTER EFFICIENCY, %	=	96.5	0	FUEL CELL INLET CO2 FRACTION	= 0.1793
PARASITIC PWR, CONTROLS&MISC, KW	=	10	0	OUTLET CO2 FRACTION	= 0.0572
FUEL PROCESSING	=			GAS TURBINE	
PREREFORM EXIT PRES, PSIA	=	17	0	TURBINE GEN NETPOWER AC, KW	= 3440
PREREFORM INLET TEMP, C	=	752	E-3 EXIT	HI TURBINE INLET TEMPERATURE, F	= 1526
STEAM/CH4 RATIO	=	1.5	0	LOW TURBINE INLET TEMPERATURE, F	= 1220
RU TEMP, F	=	1100	0	HIGH TURBINE POWER, KW	= 8035
GAS TURBINE			0	LOW TURBINE POWER, KW	= 1315
GAS TURBINE COMP EFF, %	=	85	0	1ST STAGE COMPRESSOR WORK, KW	= 1827
GAS TURBINE TURB EFF, %	=	90	0	2ND STAGE COMPRESSOR WORK, KW	= 2002
GT COMPRESSOR PRESS RATIOS	=	2.63	0	3RD STAGE COMPRESSOR WORK, KW	= 2011
EACH INTERCOOLER PRESS LOSS, PSI	=	1	0		
COMPRESSOR DUCT AND INLET LOSSES, %	=	3	0		
PRESSURE LOSS, COMP OUT TO TURB IN, PSI	=	4	0		
PRESSURE LOSS, E-9, PSI	=	1	0		
1ST TURBINE STAGE OUTLET PRESSURE, PSIA	=	23	0		
TURBINE EXIT DIFFUSER LOSSES, %, 1ST/2ND	=	7/5	0		
GENERATOR EFFICIENCY, %	=	98	0		
TURBINE STAGE HEAT LOSS, BTU/HR	=	10000	0		
HEAT EXCHANGER SUMMARY		REFERENCE	+/- DEVIATION	REQUIRED HEAT EXCHANGER EFFECTIVENESS	
E-1 SECOND STAGE AIR HEATER	COLD SIDE EXIT	1058	0	E-1	= 0.68
E-2 PROCESSED FUEL REHEATER	COLD SIDE EXIT	932	0	E-2	= 0.86
E-3 FUEL /STEAM HEATER	COLD SIDE EXIT	752	0	E-3	= 0.75
E-4 FIRST STAGE AIR HEATER	COLD SIDE EXIT	816	0	E-4	= 0.96
E-5 BOILER	COLD SIDE EXIT	239	0	E-5	= 0.81
E-6 NATURAL GAS HEATER	COLD SIDE EXIT	212	0	E-6	= 0.81
E-7 FEEDWATER HEATER	COLD SIDE EXIT	203	0	E-7	= 0.80
E-8 TURBINE INLET HEATER	COLD SIDE EXIT	1526	0	E-8	= 0.89
E-9 TURBINE INLET REHEATER	COLD SIDE EXIT	1220	0	E-9	= 0.84
E-10 INTERCOOLER	HOT SIDE EXIT	122	0	E-10	= 0.79
E-11 INTERCOOLER	HOT SIDE EXIT	122	0	E-11	= 0.86
E-12 COOLING TOWER	COLD SIDE EXIT	86	0	E-12	= 0.81
				PROCESS WATER TOTAL, GAL/MIN	= 16

Table 2.2: High Efficiency Power Plant Heat and Mass Balance Summary, continued

STATION		TEMP DEG F	PRESS PSIA	ENTHALPY BTU/HR	COMPOSITION, VOLUME							FLOW MOLES/HR	FLOW LBS/HR
NO	DESCRIPTION				FRACTION								
					H2	H2O	CH4	CO	CO2	O2	N2		
1	NATURAL GAS IN	59.0	29.70	-7,949,462	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
2	DESULFUR NAT GAS	15.0	24.70	-7,949,462	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
3	HEATED NAT GAS	212.0	24.60	-7,551,780	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
4	FUEL/STEAM/RECYCLE	233.7	19.20	-51,454,583	0.0012	0.5991	0.3835	0.0000	0.0083	0.0000	0.0080	752.02	13,187
5	PREREFORMER INLET	752.0	19.00	-47,683,213	0.0012	0.5991	0.3835	0.0000	0.0083	0.0000	0.0080	752.02	13,187
6	PREREFORMER EXIT	611.3	17.00	-47,682,947	0.0748	0.5448	0.3539	0.0001	0.0264	0.0000	0.0078	774.58	13,187
7	FUEL/STEAM TO E-2	611.3	16.71	-46,948,630	0.0742	0.5406	0.3511	0.0001	0.0262	0.0000	0.0077	768.57	12,984
8	FUEL/STEAM FROM E-2	932.0	16.61	-44,362,077	0.0742	0.5406	0.3511	0.0001	0.0262	0.0000	0.0077	768.57	12,984
9	FUEL TO STACK Rus	932.0	16.60	-44,362,077	0.0746	0.5357	0.3555	0.0001	0.0264	0.0000	0.0078	768.57	12,984
10	FUEL FROM Rus	1100.0	15.60	-30,524,258	0.5111	0.2058	0.1256	0.0734	0.0784	0.0000	0.0057	1,045.61	12,984
11	FUEL TO ANODES	1100.0	15.60	-30,524,258	0.5111	0.2058	0.1256	0.0734	0.0784	0.0000	0.0057	1,045.61	12,984
12	FUEL FROM ANODES	1170.0	15.52	-243,537,416	0.0715	0.3897	0.0000	0.0423	0.4938	0.0000	0.0027	2,195.09	66,199
13	FUEL TO BURNER	1170.0	15.50	-243,537,416	0.0715	0.3897	0.0000	0.0423	0.4938	0.0000	0.0027	2,195.09	66,199
14	BURNER PREMIX	1124.5	15.45	-199,470,000	0.0232	0.1332	0.0000	0.0137	0.1623	0.1398	0.5278	6,765.09	197,763
15	BURNER EXHAUST	1585.3	15.35	-199,469,960	0.0000	0.1593	0.0000	0.0000	0.1793	0.1236	0.5377	6,640.15	197,763
16	EXHAUST FROM E-8	1309.4	15.27	-216,413,113	0.0000	0.1593	0.0000	0.0000	0.1793	0.1236	0.5377	6,640.15	197,763
17	CATHODE INLET	1035.8	15.19	-232,676,546	0.0000	0.1593	0.0000	0.0000	0.1793	0.1236	0.5377	6,640.15	197,763
18	CATHODE EXHAUST	1173.6	15.11	-94,334,827	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
19	EXHAUST TO E-1	1173.6	15.15	-94,334,827	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
20	EXHAUST TO E-2	982.1	15.05	-102,758,864	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
21	EXHAUST TO E-3	922.3	15.00	-105,345,417	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
22	EXHAUST TO E-4	834.1	14.95	-109,116,787	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
23	EXHAUST TO E-5	446.8	14.85	-125,129,423	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
24	EXHAUST TO E-6	248.1	14.80	-133,024,387	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
25	EXHAUST TO E-7	238.0	14.75	-133,422,069	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
26	EXHAUST FROM SYSTEM	208.6	14.70	-134,573,876	0.0000	0.1993	0.0000	0.0000	0.0572	0.0711	0.6724	5,309.99	144,548
27	PROCESS AIR IN	59.0	14.70	9,478,849	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
28	1ST STAGE COMP IN	59.0	14.45	9,478,849	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
29	1ST STAGE COMP OUT	253.7	38.01	15,714,514	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
30	2ND STAGE COMP IN	122.0	35.87	11,490,654	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
31	2ND STAGE COMP OUT	334.3	94.35	18,322,460	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
32	3RD STAGE COMP IN	122.0	90.52	11,490,654	0.0000	0.0583	0.0000	0.0000	0.0091	0.6273	2.3636	4,570.00	131,564
33	3RD STAGE COMP OUT	335.4	238.06	18,355,459	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
34	PREHEATER E-4 OUT	816.0	236.73	34,368,095	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
35	PREHEATER E-1 OUT	1058.0	235.39	42,792,133	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
36	1ST TURBINE IN	1526.0	231.68	59,735,286	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
37	1ST TURBINE OUT	755.6	25.81	32,302,844	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
38	2ND TURBINE IN	1220.0	23.00	48,566,276	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564
39	2ND TURBINE OUT	1094.0	15.50	44,067,163	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,570.00	131,564

Table 2.2: High Efficiency Power Plant Heat and Mass Balance Summary, continued

STATION		TEMP DEG F	PRESS PSIA	ENTHALPY BTU/HR	COMPOSITION, VOLUME							FLOW	
NO	DESCRIPTION				FRACTION							MOLES/HR	LBS/HR
					H2	H2O	CH4	CO	CO2	O2	N2		
40	PROCESS WATER IN	59.0	30	-52,214,531	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
41	TREATED WATER	59.0	24	-52,214,531	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
42	FEEDWATER HTR OUT	203.0	23	-51,062,724	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
43	STEAM FROM BOILER	239.0	22	-43,167,937	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
44	STEAM TO EJECTOR	239.0	21.5	-43,167,937	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
45	FUEL RECYCLE	611.3	17	-734,257	0.0742	0.5407	0.3512	0.0000	0.0262	0.0000	0.0077	12.02	203
46	STEAM/ RECYCLE MIX	250.1	19.5	-43,902,319	0.0020	0.9879	0.0093	0.0000	0.0007	0.0000	0.0002	456.02	8,202
47	COOLING PMP INLET	86.0	29	-608,992,883	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5,200.00	93,683
48	COOLING PMP EXIT	86.0	36	-608,992,883	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5,200.00	93,683
49	COOLANT TO E-10	86.0	36	-234,228,032	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2,000.00	36,032
50	COOLANT FROM E-10	203.2	34	-230,004,171	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2,000.00	36,032
51	COOLANT TO E-11	86.0	36	-374,764,851	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3,200.00	57,651
52	COOLANT FROM E-11	204.5	34	-367,933,045	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3,200.00	57,651
53	COOLANT TO E-12	204.0	34	-597,937,610	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5,200.00	93,683
54	AIR TO TOWER	59.0	14.7	248,897,563	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	119,999.88	3,454,636
55	AIR FROM TOWER	72.2	14.7	259,952,836	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	119,999.88	3,454,636

HEAT & MASS BALANCE AROUND THE ENTIRE PLANT
SYSTEM ENERGY AND MOLE BALANCE

STATION		ENERGY BTU/HR	MASS, LB/HR	MOLES				
				H2	O2	C	N2	
IN	FUEL IN	1	-7,949,462	4,985	568.3	5.9	290.1	5.9
	PROCESS AIR IN	27	9,478,849	131,564	45.7	982.5	13.7	3564.6
	WATER IN	40	-52,214,531	7,999	444.0	222.0	0.0	0.0
	COOLING AIR IN	54	248,897,563	3,454,636	1200.0	25799.8	360.0	93599.9
	TOTAL		198,212,419	3,599,184	2258.0	27010.3	663.8	97170.4
OUT	FUEL CELL DC POWER		60,133,647					
	EXHAUST	26	-134,573,876	144,548	1058.0	1210.5	303.8	3570.5
	COOLING AIR OUT	55	259,952,836	3,454,636	1200.0	25799.8	360.0	93599.9
	GT POWER		11,978,915		2258.0	27010.3	663.8	97170.5
	GT HEAT LOSS		20,000					
	STACK HEAT LOSS		700,000					
	TOTAL		198,211,523	3,599,184				
	ERROR (IN-OUT)		896	0	0.0	0.0	0.0	0.0
	(IN-OUT)/ IN , %		0.0005					

2.2 Task 2: Equipment Sizing and Specification

The objective of this task was to develop specifications for the system and individual major equipment items adequate for general disclosure and to the detail necessary to make judgments about system feasibility within 2010 time frame. Specifications were also required to a sufficient level of detail to allow the generation of an accurate cost estimate in Task 3.

The equipment sizing work had its basis in the process modeling activity of Task 1. Once the system was selected and refined, and a complete process model was developed, the equipment specifications could be derived from the modeled predictions of equipment duties. In the case of this project two models were available - ChemCAD^(TM) and EXCEL^(TM) - which allowed for cross-checking of the system parameters.

With respect to feasibility within the next decade, there is no question that all of the specified equipment can be available in this time frame. As noted above, the new hybrid system eliminated the developmental items which existed in the earlier system. The equipment in the system falls into the following categories:

- Developmental Fuel Cells, which are projected to commercially available in the next two years, and performing at the projected level in the next four years. The DC power section includes 12 4-stack fuel cell modules with exactly the same design as planned for the baseline simple cycle MW scale powerplants.
- Multi-stage turbomachinery, which is not commercially available in exactly these sizes now, but which embodies conventional technology. This equipment could certainly be made available whenever market conditions or policy direction trigger the design and tooling investment.
- Conventional process equipment, such as heat exchangers, etc.

Perhaps the most developmental non-fuel cell item is the anode exhaust oxidizer. This is a catalytic reactor which reacts anode tail gas with air. Similar units have been built for the 2MW Santa Clara plant and ERC's full height stack test facility. The only difference here is that the flue gas temperature is hotter, 1600°F vs 1300°F. This can be handled with a staged approach, in which some of the fuel is reacted with air to provide a 1300 °F flue gas (in a reactor similar to those used at SCDP and ERC), and additional fuel can then be added in non-catalytic sections of the oxidizer to provide the higher temperatures from auto-ignition.

The equipment specifications are summarized in Table 2.3, which lists the equipment, capacities, materials of construction, and design characteristics for the major equipment items. The configuration of equipment in the plant has been evaluated and is illustrated in Figure 2.3, which shows the preliminary power plant layout.

Table 2.3: Major Equipment List

ITEM #	MAJOR EQUIPMENT ITEM	UNIT CAPACITY	MATERIAL OF CONSTRUCTION	DESIGN CHARACTERISTICS
	AREA 1 - FUEL CELL SUB-SYSTEM			
1	FUEL CELL MODULES	12 MODULES, 4 STACKS/MODULE		380 CELLS/STACK, CELL AREA 0.78M ²
2	DESULFURIZER	1872 SCFM Natural Gas	CARBON STEELS	ACTIVATED CHARCOAL
3	ANODE EXHAUST OXIDIZER	27.6 MMBTU/HR	STAINLESS STEELS	CATALYTIC INLET SECTION
4	HEAT RECOVERY UNIT (2 REQUIRED)			
4.1	E-1 SECOND STAGE AIR HEATER	4.5 MMBTU/HR, EFFECTIVENESS=0.68	STAINLESS STEEL	FINNED TUBES, MULTI-PASS, CROSS COUNTER FLOW,
4.2	E-2 PROCESSED FUEL HEATER	1.25 MMBTU/HR, EFFECTIVENESS=0.86	STAINLESS STEEL	FINNED TUBES, MULTI-PASS, CROSS COUNTER FLOW,
4.3	E-3 FUEL/STEAM HEATER	1.9 MMBTU/HR, EFFECTIVENESS=0.75	STAINLESS STEEL	FINNED TUBES, MULTI-PASS, CROSS FLOW
4.4	E-4 FIRST STAGE AIR HEATER	8.85 MMBTU/HR, EFFECTIVENESS = 0.96	STAINLESS STEEL	FINNED TUBES, MULTI-PASS, CROSS COUNTER FLOW
4.5	E-5 BOILER	3.85 MMBTU/HR, EFFECTIVENESS = 0.81	STAINLESS STEEL	FINNED TUBES, 1 PASS, CROSS FLOW
4.6	E-6 NATURAL GAS HEATER	0.2 MMBTU/HR, EFFECTIVENESS=0.81	STAINLESS STEEL	FINNED TUBES, 1 PASS, CROSS FLOW,
4.7	E-7 FEEDWATER HEATER	0.6 MMBTU/HR, EFFECTIVENESS =0.80	STAINLESS STEEL	FINNED TUBES, 1 PASS, CROSS FLOW
5	WATER TREATMENT SYSTEM	5 MHP, 4 GPM R.O. FEED PUMP, (2) 7 GPM, .75 MHP TRANSFER PUMPS, 2500 GAL WATER STORAGE TANK	MISC	PACKAGED ASSEMBLY
6	STEAM JET EJECTOR	DELTA P = 2 PSI		
7	PRECONVERTER	1851 SCFM Natural Gas		
8	PIPING & PIPE INSULATION		STAINLESS STEEL	

Table 2.3: Major Equipment List, continued

ITEM #	MAJOR EQUIPMENT ITEM	UNIT CAPACITY	MATERIAL OF CONSTRUCTION	DESIGN CHARACTERISTICS
9	POWER CONDITIONING SYSTEM	17 MVA		1200 VDC IN / 440 VAC 3 PHASE OUT
10	DC CABLING	1250 AMPS/STACK MODULE	NI / CU	1200 VOLTS
11	MISC ELECTRICAL EQUIPMENT			
12	CONTROLS & INSTRUMENTS			
	AREA 2 - GAS TURBINE CYCLE			
13	GAS TURBINE			PACKAGED UNIT BY GAS TURBINE VENDOR
13.1	ELECTRIC GENERATOR	3.2MVA		
13.2	1ST STAGE COMPRESSOR	1849 hp		
13.3	2 ND STAGE COMPRESSOR	2882 hp		
13.4	3 RD STAGE COMPRESSOR	2787 hp		
13.5	HIGH PRESSURE TURBINE	10,864 hp		
13.6	LOW PRESSURE TURBINE	1568 hp		
14	E-10 FIRST INTERCOOLER	4.14 MMBTU/HR, EFFECTIVENESS=0.79	ALUMINUM	OFF ENGINE- PLATE/FIN COUNTER FLOW,
15	E-11 SECOND INTERCOOLER	7.1 MMBTU/HR, EFFECTIVENESS=0.86	ALUMINUM	OFF ENGINE -PLATE/FIN COUNTER FLOW,
16	E-12 COOLING UNIT	11.3 MMBTU/HR, EFFECTIVENESS=0.81	COPPER	FINNED TUBES,, FORCED DRAFT, DRY , 15 - 1.5 HP FANS
17	COOLANT PUMP	100 GPM @ 25' HEAD		3 PUMPS, 2 OPERATING , ONE SPARE
18	AIR FILTER	31,200 SCFM		
19	START BURNER			
20	E-8 TURBINE INLET HEATER(2 REQUIRED)	9.08 MMBTU/HR, EFFECTIVENESS=.89	INCONEL 600	5/8" BARE TUBES, 3 PASS, CROSS COUNTER FLOW, 5378 FT ² SURFACE
21	E-9 TURBINE REHEATER (2 REQUIRED)	7.8 MMBTU/HR, EFFECTIVENESS=.84	STAINLESS STEEL	5/8" BARE TUBES, 3 PASS, CROSS COUNTER FLOW, 6239 FT ² SURFACE
22	PIPING & PIPE INSULATION			
	AREA 3- OVERALL PLANT			
23	OUTPUT TRANSFORMER	20.2 MVA		440 VAC IN / 13.8KV OUT
24	SWITCHGEAR & MISC ELECTRICAL			
25	POWER PLANT CONTROLLER			MICROPROCESSOR WITH CRT INTERFACE
26	UPS			5 kW FOR CONTROL POWER, 24 HOUR BATTERY

Figure 2.3: Preliminary Layout of 20MW Hybrid Powerplant

2.3 Task 3: Cost Estimating

The equipment list and preliminary layout were used to develop a capital cost estimate for the powerplant. The costs were estimated by various methods, depending on the type of cost element under consideration. For equipment costs, the following approaches were used:

- Budgetary estimates from potential suppliers were sought and obtained for equipment which was very specific to this powerplant design. This was done for the heat exchangers in the HRSG because of their unique duties and, in some cases, their high required effectiveness. This was also done for the dry cooling tower used to remove heat from the air compressors. The turbine section of the powerplant was also estimated this way, using a budgetary estimate provided by Allison Engine Company. Allison provided a "fully learned" estimate of \$600 per kW of turbine output. It was noted that this does not include first-of-a-kind development and tooling costs, which would impact early units depending on how those costs are covered and what production volumes are achieved. The fully learned estimate is consistent with the cost methodology of this study ("mature technologies and integration techniques, not first-of-a kind" per the Reporting Requirements), and was used for the plant cost estimate.
- Richardson Process Plant Construction Estimating Standards was used to estimate the cost of piping and insulation, and to estimate construction and installation costs.
- ERC's 3 MW commercial power plant cost estimate was used as a source of equipment cost data for items which would simply scale up to the larger plant. The cost elements were escalated from 1995 dollars to mid 1998 dollars using escalation factors from the Plant Cost Index of Chemical Engineering magazine (McGraw-Hill). Scale-up to the size required for the 20MW power plant was done based on the ratio of process flow between the larger equipment and the 3MW plant equipment. This scaleup factor was used with a cost power factor to derive the cost of the larger unit. The cost power factors were obtained from "*Design Cost Factors for Scaling-up Engineering Equipment*", S.S. Remer & L.H. Chai, Chemical Engineering Progress, August 1990.
- ERC's Internal database of costs for similar equipment based on other ERC projects which are collecting similar types of equipment costs.

The estimate for equipment and installation costs is summarized Table 2.4. Additional costs (land, startup, training, etc) are not included in Table 2.4, but were estimated in the cost of energy calculation, described next.

Table 2.4: Power Plant Equipment and Installation Cost Summary

ITEM	MAJOR EQUIPMENT ITEM	1995\$ 3.08 MW COST	ESCLTMN FCTR 95 TO 98\$	EQUIP COST/UNIT	COST BASIS	20MW FACTOR	COST FACTOR	COST/UNIT 20MW PLANT	SALES TAX/ UNIT	FREIGHT COST/UNIT	INSTALLATION MHRS COST/UNIT	TOTAL COST/UNIT	QUANTITY	TOTAL COST, \$	COST \$/KW	
AREA 1 - FUEL CELL SUB-SYSTEM																
1	FUEL CELL MODULES	\$509,748	1.01	\$514,845	"3"	0.96	0.96	\$493,119	\$0	\$14,250	1000	\$31,000	\$538,369	12	\$6,460,428	316.5
2	DESULFURIZER	\$25,500	1.05	\$26,775	"3"	6.25	3.48	\$93,101	\$0	\$1,250	16	\$496	\$94,847	1	\$94,847	4.6
3	ANODE EXHAUST OXIDIZER	\$105,352	1.05	\$110,620	"3"	3.27	2.24	\$247,422	\$0	\$1,250	40	\$1,240	\$249,912	2	\$499,823	24.5
4	HEAT RECOVERY UNIT, INCLUDES				"1"			\$440,000	\$0	\$5,004	200	\$6,200	\$451,204	2	\$902,408	44.2
4.1	E-1 SECOND STAGE AIR HEATER															0.0
4.2	E-2 PROCESSED FUEL HEATER															0.0
4.3	E-3 FUEL /STEAM HEATER															0.0
4.4	E-4 FIRST STAGE AIR HEATER															0.0
4.5	E-5 BOILER															0.0
4.6	E-6 NATURAL GAS HEATER															0.0
4.7	E-7 FEEDWATER HEATER															0.0
5	WATER TREATMENT SYSTEM	\$41,087	1.05	\$43,141	"3"	5.95	4.09	\$176,585	\$0	\$6,000	100	\$3,100	\$185,685	1	\$185,685	9.1
6	STEAM JET EJECTOR	\$13,200	1.05	\$13,860	"3"	2.71	1.68	\$23,281	\$0	\$100	4	\$124	\$23,505	2	\$47,011	2.3
7	PRECONVERTER	\$17,172	1.05	\$18,031	"3"	2.71	1.97	\$35,527	\$0	\$200	16	\$496	\$36,223	2	\$72,446	3.5
8	SS PIPING& PIPE INSULATION				"2"			\$595,856	\$0	INCLUDED		INCLUDED	\$595,856	2	\$1,191,712	58.4
9	POWER CONDITIONING SYSTEM	\$397,539	1.03	\$409,465	"3"	2.76	2.49	\$1,020,936	\$0	\$6,000	100	\$3,100	\$1,026,936	2	\$2,053,871	100.6
10	DC CABLING/CONDUIT				"2"			\$22,500	\$0	INCLUDED		INCLUDED	\$22,500	1	\$22,500	1.1
11	MISC ELECTRICAL EQUIPMENT	\$15,000	1.03	\$15,450	"3"	2.76	2.04	\$31,444	\$0	\$500	100	\$3,100	\$34,544	2	\$69,088	3.4
12	CONTROL VALVES &INSTRUMENTS	\$123,600	0.99	\$122,364	"3"	2.71	1.97	\$241,104	\$0	\$3,000	140	\$4,340	\$245,444	2	\$490,888	24.1
AREA 2 - GAS TURBINE CYCLE																
1	GAS TURBINE/GENERATOR				"1"			\$3,000,000	\$0	\$5,200	200	\$6,200	\$3,011,400	1	\$3,011,400	147.5
2	E-10 FIRST INTERCOOLER				"4"			\$30,000	\$0	\$341	20	\$620	\$30,961	1	\$30,961	1.5
3	E-11 SECOND INTERCOOLER				"4"			\$40,000	\$0	\$278	20	\$620	\$40,898	1	\$40,898	2.0
4	E-12 COOLING TOWER				"1"			\$25,000	\$0	\$1,500	60	\$1,860	\$28,360	1	\$28,360	1.4
5	COOLANT PUMP				"2"			\$4,950	\$0	\$28	23	\$713	\$5,691	3	\$17,073	0.8
6	AIR FILTER			\$4,052	"5"	11.00	5.11	\$20,693	\$0	\$400	24	\$744	\$21,837	1	\$21,837	1.1
7	OFF ENGINE START BURNER			\$6,876	"5"	5.20	3.07	\$21,097	\$0	\$1,000	40	\$1,240	\$23,337	2	\$46,674	2.3
8	TURBINE INLET HEATER UNITS															0.0
8.1	E-8 TURBINE INLET HEATER				"4"			\$210,000	\$0	\$1,600	20	\$620	\$212,220	2	\$424,440	20.8
8.2	E-9 TURBINE REHEATER				"4"			\$120,000	\$0	\$1,800	20	\$620	\$122,420	2	\$244,840	12.0
9	SS PIPING& PIPE INSULATION				"2"			\$261,710	\$0	INCLUDED		INCLUDED	\$261,710	1	\$261,710	12.8
AREA 3 - OVERALL PLANT																
1	TRANSFORMERS&MISC ELEC	\$26,400	1.03	\$27,192	"3"	5.52	3.31	\$89,902	\$0	\$6,000	250	\$7,750	\$103,652	1	\$103,652	5.1
2	MOTOR CONTROL CENTER	\$15,700	1.03	\$16,171	"3"	1.00	1.00	\$16,171	\$0	\$2,000	8	\$248	\$18,419	1	\$18,419	0.9
3	BULKS(ELECTRICAL)	\$74,200	1.03	\$76,426	"3"	5.52	3.31	\$252,679	\$0	\$3,000	2000	\$62,000	\$317,679	1	\$317,679	15.6
4	POWER PLANT CONTROLLER	\$28,000	0.99	\$27,720	"3"	3.00	3.00	\$83,160	\$0	\$500	500	\$15,500	\$99,160	1	\$99,160	4.9
5	CONTROL CONDUIT	\$11,400	0.97	\$11,058	"3"	5.52	3.31	\$36,560	\$0	\$1,000	500	\$15,500	\$53,060	1	\$53,060	2.6
6	UPS	\$25,500	1.03	\$26,265	"3"	3.00	2.16	\$56,671	\$0	\$2,000	50	\$1,550	\$60,221	1	\$60,221	3.0
7	I&C AIR SYSTEM	\$34,766	1.08	\$37,547	"3"	5.42	3.55	\$133,421	\$0	\$600	50	\$1,550	\$135,571	1	\$135,571	6.6
8	MISC CRBN STEEL PIPNG&VALVES	\$10,500	0.99	\$10,395	"3"	5.42	3.16	\$32,815	\$0	2000	125	\$3,875	\$38,690	1	\$38,690	1.9
9	FIRE PROTECTION(SUBCNTRCT)	\$51,100	1.01	\$51,611	"3"	6.00	3.38	\$174,536	\$0	INCLUDED		INCLUDED	\$174,536	1	\$174,536	8.6
10	CIVIL WORKS	\$85,400	1.04	\$88,816	"3"	6.00	3.38	\$300,354	\$0	INCLUDED		INCLUDED	\$300,354	1	\$300,354	14.7
TOTALS														\$17,520,242	858.4	

TOTAL INSTALLATION COST =

\$537,912

Cost Basis Code Explanations:

"1" - Budgetary estimate from potential supplier

"2" - Estimate from conceptual design based on Richardson Process Plant Construction Estimating Standards

"3" - Estimate based on appropriate factor from detailed design of ERC 3 MW commercial plant design and cost, independently reviewed in DOE due diligence activity.

"4" - Estimate based on design sizing and cost /lb from quotations on similar equipment

"5" - Estimate based on appropriate factor from design and cost estimate for other application

The process model of the power plant was used to estimate process consumables, and manning forecasts were made to estimate operating labor costs. Fixed and variable cost estimates for the plant are summarized in Table 2.5

Table 2.5: Hybrid Plant Operating & Maintenance Costs

Fixed Costs	<u>Annual Cost</u>
Operating Labor (1000 Mhrs/Yr)	40,800
Maintenance Labor (1000 Mhrs/Yr)	45,600
Management Labor (400 Mhrs/Yr)	24,000
Other (non-staff)	10,000

Total Fixed Costs	120,400
Variable Costs	
Consumables	
Water & Sewer (\$1.7/1000 gallons)	12,520
Catalysts and Sorbents	48,130
Water Treatment	50,900
Miscellaneous	17,400
Maintenance During Plant Shutdown	160,968
(estimated @ 2% of fuel cell BOP cost)	-----
Total Variable Costs	289,918
Total Fixed and Variable Costs	410,318
Fuel Cell Module Replacement (5 year intervals)	6,460,428
25 year annualized cost of 4 replacements	1,033,668

These O&M costs were combined with estimates of additional cost, such as start-up, training, home office costs, etc to derive a cost of energy (COE) estimate, using the calculation assumptions specified in the Reporting Requirements. A summary of the COE calculation is shown in Table 2.6.

A cost of energy of 4.45 ¢/kWh was estimated, and this is the value used in comparisons and sensitivity studies in Task 4. An additional exercise was done in which a learning-type cost reduction occurred over the course of the 25-year analysis period, reducing the cost of replacement stack modules. The estimated COE with replacement stacks on 95, 90, and 85 percent learning curves is shown at the bottom of Table 2.6

Table 2.6: Cost of Energy Calculation for Hybrid Power Plant

		\$	\$/KW
EQUIPMENT & INSTALLATION COST, TABLE 2.4		\$17,520,242	858.4
START-UP & TRAINING (1)	2%	\$350,405	17.2
LAND 1 ACRE		\$10,000	0.5
HOME OFFICE COST(2)	3%	\$525,607	25.8
ALLOCABLE COSTS(3)	3%	\$525,607	25.8
PROFIT	5%	\$876,012	42.9
TOTAL CAPITAL REQUIREMENT		\$19,807,873	970.5
CAPITAL CHARGE RATE (25 YEAR),%		15	
CAPACITY FACTOR ,%		92	
FUEL COST, \$/MMBtu(HHV)		3	
EFFICIENCY (LHV),%		71.1	
EFFICIENCY (HHV),%		63.99	
FUEL CELL RATING, kW		17002.00	
GAS TURBINE RATING,kW		3440.00	
POWER PLANT RATING, KW		20,411	
YEARLY POWER GENERATION, KWHS		164,496,331	
COST OF ELECTRICITY(25 YEAR LEVELIZED)Constant \$			
		Yearly Cost	Cents/kWhr
CAPITAL RECOVERYCOST		\$2,971,181	1.806
OPERATING & MAINTENANCE COST			
FC FIXED (Tab. 2.5)		\$120,400	0.073
FC VARIABLE (Table 2.5)		\$289,918	0.176
GAS TURBINE, 0.01\$/kWhr		\$277,236	0.169
FUEL COST		\$2,632,219	1.600
FUEL CELL MODULE REPLACEMENT(ANNUALIZED)		\$1,033,668	0.628
COST OF ENERGY	TOTALS	\$7,324,623	4.453
TOTAL COST OF ELECTRICITY	LEARNING RATE(4)		
WITH PRODUCTION LEARNING	5%	\$7,143,154	4.3424
ON REPLACEMENT MODULES	10%	\$6,959,767	4.2310
	15%	\$6,864,745	4.1732
(1) Includes plant commissioning, acceptance testing, & Plant Buyers O&M staff training			
(2) Includes project management, Engineering & Site specific design, procurement, finance, clerical			
(3) Includes costs for legal and contracting, insurance, marketing, warranty reserves, interest, royalty			
(4) Production cost reduced by learning rate for each doubling of production quantity			

2.4 Task 4: Financial Analysis and Risk Analysis

2.4.1 Comparison and Sensitivity Analyses

This task called for the development of a financial analysis of the system. This includes an analysis of sensitivity of the cost of electricity (COE) to fuel price assuming the natural pipeline gas costs of \$1 to \$6 per million British thermal units (BTU's). A risk assessment of the costs estimated for each major cost category was also done.

In addition to the COE sensitivity analysis identified in the project SOW, the Reporting Requirements also asked for comparison with conventional generating equipment using \$3/MMBtu fuel. In this task a COE for a combined cycle power plant of similar size was estimated, and the estimate is summarized in Table 2.7. In this analysis the COE for the conventional powerplant is 5 to 12 percent more than the hybrid system, depending on whether or not replacement stack learning cost reduction is considered.

These same sets of assumptions were used in the sensitivity analysis, in which the conventional combined cycle plant was compared to the hybrid (in this case without replacement stack learning cost reduction) over a range of fuel costs. The results of this analysis are shown in Figure 2.4, which shows that even without stack cost reduction from learning assumptions, the plant COE is competitive with the conventional combined cycle plant for gas costs of \$2/MMBtu and higher.

Figure 2.4
Cost of Energy Comparison with Conventional Combined Cycle

Table 2.7
Cost of Energy Calculation for Conventional Plant

Reference: 1. Gas Turbine World Handbook General Electric STEG LM 116		
	\$	\$/KW
EQUIPMENT & INSTALLATION COST, Ref 1.	\$15,418,200	840.0
NATURAL GAS COMPRESSOR	\$594,700	32.4
START-UP & TRAINING (1)	2% \$320,258	17.4
LAND 1 ACRE	\$10,000	0.5
HOME OFFICE COST(2)	3% \$480,387	26.2
ALLOCABLE COSTS(3)	3% \$480,387	26.2
PROFIT	5% \$800,645	43.6
TOTAL CAPITAL REQUIREMENT	\$18,104,577	986.4
CAPITAL CHARGE RATE (25 YEAR),%	15	
CAPACITY FACTOR ,%	92	
FUEL COST, \$/MMBtu(HHV)	3	
EFFICIENCY (LHV),%(5)	48.8	
EFFICIENCY (HHV),%	43.93	
GAS TURBINE RATING,kW	13100.00	
STEAM PLANT RATING, kW	5300.00	
POWER PLANT RATING, kW(5)	18,355	
YEARLY POWER GENERATION, KWHRS	147,926,616	
COST OF ELECTRICITY(25 YEAR LEVELIZED)Constant \$		
	Yearly Cost	Cents/kWhr
CAPITAL RECOVERYCOST	\$2,715,687	1.836
OPERATING & MAINTENANCE COST		
FIXED (4.7\$/kW yr)(4)	\$86,269	0.058
VARIABLE (4.7MILLS/KWHR)	\$695,255	0.470
FUEL COST	\$3,447,757	2.331
TOTALS	\$6,944,967	4.695
(1) Includes plant commisioning, acceptance testing, & Plant Buyers O&M staff training (2) Includes project management, Engineering & Site specific design, procurement, finance, clerical (3) Includes costs for legal and contracting, insurance, marketing, warranty reserves, interest, royalty (4) Based EPRI TAG for 120MW combined cycle escalated 20% for 1998 \$ (5) Corrected for 345kW gas compressor power consumption		

2.4.2 Risk Analysis

The cost estimate was evaluated in a risk analysis effort, in which probabilistic curves were assigned to individual cost estimate line items, and the impact on projected system cost was assessed. Crystal BallTM software was used for this analysis. This software is a Microsoft EXCELTM add-in which runs over the spreadsheet based cost estimate and uses a Monte-Carlo simulation to evaluate the overall probability of meeting or exceeding the projected cost. A similar analysis is done annually on the cost projection for the baseline simple cycle commercial product as part of the due diligence activity under the PDI program.

For the purposes of this project, the cost risks were estimated at the level of line items in the summary forecast, as presented earlier in Table 2.4. Each of the line item estimates was evaluated in terms of the probability of the actual cost meeting or exceeding the estimate. Distribution curves were developed for each line item, and fed into a Monte-Carlo simulation to assess the probability of achieving the projected cost. The rationale for the major line item probability assumptions was as follows:

Fuel Cell Modules

In the case of the fuel cell modules, the distribution which was selected was a Weibull distribution which was shaped to resemble the distribution derived from a detailed analysis in the last due-diligence effort. That effort evaluated cost probabilities for components and raw materials in the stacks and stack modules, and developed a predicted probability curve. That analysis indicated a slight probability that the stack module costs could be less than the value used in the estimate due to the impact of potential cost reductions from ongoing manufacturing process development.

Gas Turbine System

A normal distribution (with a 10% standard deviation) was assigned to the gas turbine part of the hybrid plant. The additional complexities of the multi-stage system provide upward cost pressure, but on the other hand the unit runs at low temperature with clean air as the working fluid. Additional design detail will be needed to identify a clear likelihood for the costs to go one way or the other beyond the current estimate provided by Allison Engine Company.

BOP Equipment Quoted Specifically For This Project

In cases where equipment cost quotes were obtained from vendors, a Weibull curve with a shape factor of 8 was used for the probability distribution. This curve essentially provides a fairly narrow distribution, with a limited likelihood for the cost to be above the mean estimate.

BOP Equipment Scaled From The 3MW System Design

For equipment which was scaled for the 3MW design, the probability distributions used in the last PDI due diligence study were used for this study (with the exception of the anode exhaust oxidizer). These were usually normal distributions with 5% standard deviations.

Anode Exhaust Oxidizer

In the case of the anode exhaust oxidizer, a Wiebull curve with a shape factor of 3 was used, and the location was set to indicate a likelihood that the cost could be higher than the estimate. This is due to the specialized application of the oxidizer in the hybrid system - operating at higher temperature and requiring a staged mixing between tail gas and air.

Once these probability assumptions were fed into the model, the program ran a Monte-Carlo simulation with 20,000 trials to assess how the assigned probability impacted the \$17,520,242 estimated installed equipment cost. The simulation projected an 80.8% probability that the system cost would be equal to or lower than the overall estimated cost. The probability distribution output from the program is shown in Figure 2.5.

Figure 2.5
Risk Analysis Probability Distribution for Powerplant Cost

3.0 CONCLUSION

The HEFPP project has identified an attractive DFC/Turbine hybrid design which offers the promise of >70% efficiency in a relatively simple system. The system is a significant improvement on earlier hybrid configurations due to the elimination of developmental equipment and the fact that it is a much more simple system. Cathode gas and anode gas recycle blowers have been eliminated. All gas supply is accomplished with the normal 15 psig natural gas pressure and the air compressor associated with the turbine equipment. High efficiency is obtained without the use of an additional steam bottoming cycle, eliminating the need for high pressure boilers (a concern with respect to unattended operation).

Two key features of our baseline simple cycle DFC product are retained: Ambient pressure operation and internal reforming, providing higher efficiency and avoiding the need for a high pressure boiler to provide fuel cell steam. The system allows the turbine pressure ratio to be set independently of fuel cell pressure considerations. Although in normal hybrid operation the turbine will be unfired, a burner could be provided in the turbine to allow independent operation of the turbine, replacing the existing fuel cell startup burner. Conceptually, the turbine section could be producing power during the fuel cell startup. Also conceptually, the turbine section can be used to load follow - utilizing stored kinetic energy - while the fuel cell is efficiently operated at constant power. This is only possible because of the decoupled nature of the fuel cell and turbine sections of the plant.

The cost estimate developed for the powerplant projected an installed equipment cost of \$858/kW. Cost of energy calculations indicated the system is cost competitive with conventional combined cycle equipment for cases where natural gas cost was \$2/MMBtu or greater. This analysis did not take into account cost credits or penalties which may be imposed as a matter of policy due to environmental or energy independence concerns. Given the likelihood of such policy items in the future, the possibility of providing products with these types of efficiencies is even more attractive that this simple cost analysis suggests.

Given the excellent results of this first phase of work, some consideration has been given to what the next steps should be. Additional work which was out of the scope of the study and which needs to be done on the design includes:

- Analysis of performance issues at partload.
- Startup, shutdown, and control issues.
- Evaluation of possible independent operation of turbine, e.g. during fuel cell heatup
- Evaluation of near-term options for proof-of-concept, field trials, and early market entry, including:

- Smaller systems. Hybrids based on ERC's market entry sub-MW, 1.5 MW and 3 MW power plants could offer very high efficiencies at their respective size levels.
- Field-test powerplants, consisting of hybrids with ERC's 200kW, 1MW, or 2MW near term field test systems.
- Detailed design of system-specific components. An advantage of the selected system is that there are no long term developmental issues in the balance of plant (like the high temperature heat exchanger from the earlier system). Certain components are unique to the hybrid system, and will require additional design specification. Examples include the anode exhaust oxidizer (which operates at a slightly higher temperature than the one in the baseline simple cycle system) and the multi-stage turbomachinery.

With these activities as a next logical step, a path forward is possible which can lead to the availability of very high efficiency power plants in the near future.

#2

High Efficiency Fossil Power Plants (HEFPP) Conceptualization Program

DE AC26-98FT34164
~~DE RA26-97FT34164~~

Final Report Volume II

DESCRIPTION AND USER'S MANUAL OF SYSTEM SIMULATION BASED ON EXCEL SPREADSHEET

March, 1999

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Preface

Volume II of the HEFPP final report provides a description of the EXCEL^(TM) model which was developed for the selected powerplant design, and gives instructions for its use. The basic system design is reviewed, along with some of the fundamental math and logic which is used in the model.

In describing the model and procedures for using it, example printouts are provided in the main body and in appendices. Some of these may look slightly different from the output from the version of the model distributed with the final report. For example, late changes in the model code were made to refine the modeling of the turbomachinery, based on feedback from Allison Engine Company. This includes changing the compressor and expander efficiencies and adding inlet and ducting losses specified by Allison.

These types of changes will be noticed by the model user, but they should not be a problem in interpreting the model or interpreting this volume of the report.

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1. Introduction

This report provides a description of the simulation model for the 20 MW high efficiency power plant system devised by Energy Research Corporation under US Department of Energy contract DE-AC26-98FT34164, High Efficiency Fossil Power Plants (HEFPP) Conceptual Program. The simulation model is based on an EXCEL 5 spread sheet and provided on a 3½" disk.

2.0 Model Description

The following sections describe the high efficiency power plant system and the simulation model, which quantifies the performance characteristics of the system.

2.1 Power plant system

The high Efficiency System is shown in Figure 1. The system includes a direct carbonate fuel cell, a gas turbine with three compressor stages and two turbine stages, an oxidizer and twelve heat exchangers. The Fuel cells are operated at near atmospheric pressure and the gas turbine has a nominal pressure ratio of 15:1. In the system natural gas is treated to remove sulfur and preheated in E-6 by system exhaust. The preheated fuel is mixed with steam from boiler E-5 and recycled processed gas, heated further in E-3, and flows to an adiabatic prereformer. In the prereformer any heavy hydrocarbons are reformed. The fuel/steam mix is heated further in E-2 and flows to the direct carbonate fuel cell stacks. In the fuel cell stacks the stream is partially reformed in special reformer units, RUs. The partially reformed fuel stream then flows to the fuel cell anodes where the methane is completely converted and the hydrogen is electrochemically converted to DC power. Heat for the endothermic reform reaction in the RUs and anodes is provided by the excess heat generated in the fuel cell reaction. The anode vent stream contains unused hydrogen, CO and CO₂, from the incoming fuel as well as product water formed in the cells and additional CO₂ transferred from the cathodes. The anode vent stream flows to a catalytic oxidizer, or burner, where the unreacted hydrogen and CO are burned with process air from the turbine exhaust. The burner exhaust flows through heat exchangers E-8 and E-9 to the cathodes where oxygen and CO₂ react, completing the electrochemical carbonate cell process. Cathode exhaust flows through heat exchangers E-1, 2,3,4,5,6, and 7 and is exhausted from the system. Process air is compressed in the three gas turbine compressor stages. Intercooler E-10 and E-11 is provided to minimize compressor work. The intercoolers are cooled by a circulating water loop that rejects heat to the atmosphere in a natural draft cooling tower.

HG:hef3a.node

Figure 1
Process Flow Diagram for 20MW High Efficiency Power Plant

The cathode exhaust in heat exchangers E-4 and E-1 heats the compressed process air. It then flows through E-8 where it is heated further and expands through the first turbine stage. The exhaust from the first turbine stage is reheated in E-9 and flows to the second stage turbine. Exhaust air from the second stage turbine flows to the burner.

2.2 General model description

The power plant system model has the EXCEL work book file name "hefplant.xls". The model establishes power output, efficiency, key process performance parameters, process flows, gas compositions, temperatures, pressures, and mass and energy balances throughout the power plant system. The model is programmed with certain power plant design assumptions which are presented as reference values. The sensitivity to each of the key reference design assumptions can be evaluated by an input parameter deviation. The model iterates the flows and energies in the system based on the parameter deviation until there is energy, atom and mass balance convergence throughout the system. The resulting impact on the power plant performance and conditions throughout the system is displayed.

The model consists of 8 linked files or sheets bound in work book file "hefplant.xls". The 8 sheets are listed in Table 1 and are displayed as tabs along the bottom of the active work book. A print out of each of the 8 sheets is presented in the appendices. The following are descriptions of each sheet presented in order as listed in Table 1. Following the description of each of the sheets is a section describing the procedures for using the EXCEL simulation model.

Table 1
Sheets included in EXCEL work book hefplant.xls

Summary
Boiler
Prereformer
Cell stack
Compressor
Air preheater
Turbine
Burner

2.3 Summary sheet

The summary sheet in the model, shown in Appendix 1 has four parts. The first part shown on the left of page 1 is a listing of the input parameters to the model, with a reference value for each parameter. The list starts at the top with the methane flow to the power plant and fuel heating value, and proceeds downward to include key parameters for the environment, the fuel cell stack, fuel processing, the gas turbine and the heat exchangers.

For certain of the heat exchangers the key parameter is the process cold side temperature, for others the parameter is heat exchanger effectiveness.

The second part of the summary sheet, shown on the right side of page one, is a listing of the output characteristics of the power plant. The list starts at the top with the net AC output power in kilowatts and proceeds downward displaying certain key characteristics for the fuel cells, and the gas turbine. Also listed are the heat exchanger effectiveness values needed to achieve the cold side output temperatures listed in the input parameter list.

The third part of the summary sheet shown on page 2 & 3 is a table listing the process conditions at each of the stations in the power plant systems as identified in Figure 1. The process parameters include the temperature, enthalpy, stream composition, the mole flow in lb-moles/hr and the mass flow in lb/hr.

The last part of the summary sheet shown on page 3 is a heat, mass and mole balance around the entire system displaying the input, output, error and error percentage. Since heat, mole and mass balances are performed in the modeling of each process in the system the overall is very accurate. There is a slight, <1000 Btu/hr out of about 20 million Btu/hr, imbalance of energy resulting from the convergence logic at each process step as described later.

Only the summary sheet is used to evaluate the effect of changing a system input parameter. The other sheets are all linked to the summary sheet and to each other. The stream characteristics, flow rate, composition and temperature, developed in one sheet are linked to the other sheets which use those characteristics. In the following file descriptions, parameters that can be varied in the model are presented in *Italics*.

2.4 Boiler sheet

The boiler file, shown in appendix 2, includes the boiler E-5, the fuel preheater E-6 and the feedwater preheater E-7. The boiler hot side exit temperature is calculated based on the assigned *steam temperature*, and an energy balance.

The fuel preheater hot side exit temperature is calculated based on the assigned values for the *cold side inlet and outlet temperatures*. The feedwater hot side exit temperature is calculated based on the assigned values of the *cold side inlet and outlet temperatures*.

2.5 Prereformer sheet

The prereformer file, shown in appendix 3, starts with the preheated fuel, steam and recycled processed gas and calculates the mixed conditions at the entrance to the prereformer inlet heater E-3. The file calculates E-3 hot side exit temperature based on the hot side inlet conditions from E-2, and the assigned *cold side exit temperature*. The file then takes the stream conditions to the prereformer and calculates the process conditions and temperature leaving the adiabatic prereformer. This is accomplished as follows. The file uses the following two equations for reforming and shift conversion to establish the exit composition.

Reforming Reaction "x"

$$\text{Where the reforming equilibrium constant } K_{pr} = \frac{(\text{PH}_2)^3 \times \text{PCO}}{\text{PCH}_4 \times \text{PH}_2\text{O}}$$

Shift Conversion "y"

$$\text{Where the shift equilibrium constant } K_{ps} = \frac{\text{PH}_2 \times \text{PCO}_2}{\text{PH}_2\text{O} \times \text{PCO}}$$

The combined reform and shift equations are solved simultaneously as follows. A CH_4 conversion fraction "x" is assumed. Then the shift fraction "y" is calculated from the above equations. Based on the calculated "y" and assumed "x", a composition at the exit of the prereformer is calculated. From this composition the reform constant is calculated and compared to the actual K_{pr} calculated at the prereformer exit temperature. The file then performs a dual iteration changing the assumed reform conversion fraction "x" each iteration until the proper K_{pr} is achieved within the preset convergence criteria.

At the same time the file iterates the exit temperature to achieve an energy balance. The iteration of reform fraction and exit temperature proceed simultaneously until both energy balance and equilibrium constant match are satisfied.

The prereformer file also includes models for the inlet preheater, E-3, and the exit heater E-2. In each heat exchanger model the hot side exit temperatures are calculated to achieve the assigned *cold side exit temperatures*.

2.6 Cell stack sheet

The cell stack file, shown in appendix 4, starts with the gas stream to the internal reforming units, RUs, within the cell stack. The file calculates an exit equilibrium composition from the RUs as previously discussed for the prereformer. The file calculates a shift and reform equilibrium constant based on the assigned *prereformer exit temperature*. The file assumes a reform conversion fraction and calculates a shift equilibrium composition based on the assumed conversion fraction. Next the file calculates a reform equilibrium constant based on the composition and compares it to the calculated constant based on the temperature. The file then iterates the assumed reform fraction until the calculated reform constant based on composition equals the reform constant based on temperature. An energy balance is then provided determining the endothermic reaction energy required by the internal reformer units.

The next step in the cell stack file is the calculation of the DC power output, hydrogen consumption, oxygen consumption and CO₂ transfer through the cells based on the assigned *cell voltage* and *current density* and the number and size of the cells. The file then takes the anode inlet stream and calculates a non equilibrium composition based on the hydrogen consumption, the water production and the CO₂ transfer within the cells. It also assumes 100% conversion of the methane in the anodes. Based on an assigned *anode exit temperature* the file calculates a shift equilibrium composition leaving the anodes. Next the file takes the cathode inlet composition, removes the oxygen consumed, and the CO₂ transferred to the anode, and calculates the cathode exit stream composition. The final step is an energy balance on the cell stack which includes the DC power output, the *stack heat loss*, the energy absorbed in the RU endothermic reaction, and the energy in the anode and cathode streams. The energy balance is used to determine the cathode exit temperature.

2.7 Compressor sheet

The compressor file shown in appendix 5 includes the models for each of the three compressor stages, the intercoolers the intercooler cooling loop pump and the natural draft cooling tower. It starts with certain parameter definitions from the summary sheet such as *compression ratio*.

The file then takes the inlet air to the first stage compressor, calculates the energy requirement for adiabatic compression and calculates the exit temperature based on an energy balance. The file then calculates the hot side and cold side exit temperatures for the first stage intercooler based on the assumed *effectiveness*. Next the file calculates the input pressure to the second stage compressor based on *intercooler pressure loss*, calculates the second stage compressor adiabatic energy requirement and calculates exit temperature by an energy balance as for the first stage. This is repeated for the second intercooler and third stage compressor. The file then determines the mix temperature of the water coolant streams from the two intercoolers and determines the hot side and cold side exit temperatures from the cooling tower based on the assigned *effectiveness*.

The last part of the compressor file calculates the parasitic power for the water pump in the intercooler cooling loop, and the overall parasitic power based on an assumed value of *parasitic power for the controls and miscellaneous* from the summary file.

2.7 Air preheater sheet

The air preheater file defines the conditions around the two air preheaters E-4 and E-1. For each heat exchanger it calculates the hot side exit temperature based on the established *cold side exit temperatures* and calculates the associated heat exchanger effectiveness.

2.9 Turbine sheet

The turbine file shown in appendix 7 includes the models for each of the two turbine stages. It starts with *turbine efficiencies* from the summary sheet. The file calculates pressure to the first turbine stage based on pressure from the compressor third stage and assumed *pressure losses through heat exchangers E-4, E-1 and E-8* from the summary sheet. It calculates the inlet pressure to the second stage turbine based on the loss through E-9. Pressure at the exit of the second turbine stage is established by pressure losses in the cell stack and the burner as well as hot side losses through heat exchangers E-8, E-9, and E-1 through E-7.

The file takes the stream characteristics to the first stage turbine, calculates the adiabatic expansion energy output in the first turbine stage, and calculates the exit temperature based on an energy balance. Next the file takes the input stream characteristics to the second turbine, calculates the second stage turbine adiabatic energy output and calculates exit temperature by an energy balance similar to the first stage.

The file then summarizes the energy requirements for the compressor stages and the turbine stages, calculates the net energy and applies the *generator efficiency* to establish the AC output of the turbine generator.

2.10 The burner sheet file, shown in appendix 8, starts with the stack anode exit stream and the stream from the exit of the second turbine stage. The mix stream temperature is calculated from an energy balance. The file then calculates the burner exhaust conditions assuming all of the hydrogen and CO are consumed. Exit temperature is calculated from an energy balance. The file establishes the exit temperature from heat exchanger E-8 based on a reference *E-8 cold side exit temperature* from the summary sheet. The file also calculates the required E-8 heat exchanger effectiveness. In a similar manner the file then establishes the exit temperature from heat exchanger E-9 based on a reference *E-9 cold side exit temperature* from the summary sheet. The file also calculates the required E-9 heat exchanger effectiveness.

3. Procedures for Model Use

3.1 Loading the program and initial EXCEL 5 settings

The following steps are recommended for use of the High Efficiency System EXCEL model.

1. Open EXCEL 5 work book file hefplant.xls provided on 3½" disk.
2. Before changing any parameter: click TOOLS, then OPTIONS
3. Under OPTIONS VIEW tab check
 - Show formula bar
 - Show status bar
 - Comments-none
 - Objects show all
4. Under WINDOWS OPTIONS tab check
 - Gridlines
 - Row and column headings
 - Outline symbols
 - Zero values
 - Horizontal scroll bar
 - Vertical scroll bar
 - Sheet tabs
 - Color automatic

5. Under the CALCULATION tab check

Manual

Put in 10,000 iterations

Maximum change 0.001

"No check mark" for recalculate before saving

Update remote references

Save external link values

3.2 Parameter sensitivity studies

1. Assign a new case number to the top slot on the summary sheet. This case number will be included on all 3 pages of the summary.

2. To evaluate an input parameter deviation: Put the + or minus deviation value in the deviation column adjacent the reference value. For example, to show the impact of increasing the turbine efficiency to 90% and the compressor efficiency to 85% as projected by Allison, put a deviation of 2 adjacent the compressor efficiency and a deviation of 7 adjacent the turbine efficiency. The result is shown in Appendix 8. An air flow deviation of -330 has been included to maintain the cell stack cathode exhaust temperature within established limits. Any number of deviations can be placed at one time, and deviations can remain from one case to another.

3. Press the F9 function key to start the calculation. The calculation will iterate until all the composition and energy balances are satisfied and the iteration stops. The new characteristics for the system will be displayed on the summary sheet. Iterate until all of the composition and energy balances are satisfied. This may take 1000 to 10,000 iterations depending on the parameter deviation input. Repeat as necessary until the parameters are steady and the iteration stops.

4. Read and print the outputs at the new input conditions in the summary file.

3.3 Cautions

1. When returning to the reference value enter the deviation as "zero". If the cell is entered as blank the program will turn all parameters to "#VALUE" from which the recovery is very tedious.

2. If the deviation is excessive or the deviation is not returned as a zero. The file may become unstable and all numbers will appear as "#VALUE". If this occurs close the hefplant.xlw file without saving. Reopen the file and reduce the magnitude of the input deviation or insure the reference value is returned by putting a zero in the deviation cell.

4.0 Description of key technical models

4.1 Specific Enthalpies of Gases

The enthalpy of for each of the gases is based on a 5th order polynomial fit from reference 6, providing excellent agreement with values from reference 2. The specific enthalpy for each of the gases is in Btu/lb mole and has an enthalpy base of 0 °K. Coefficients for the 5th order polynomial equations are listed in Table 1.

TABLE 1
POLYNOMIAL ENTHALPY CORRELATION.
Enthalpy, Btu/ lb mole = $a + bT + cT^2 + dT^3 + eT^4 + fT^5$
Where T is in degrees fahrenheit

Gas	a	b	c	d	e	f
O2	3192	6.88	0.0005923	1.452E-07	-1.38E-10	2.596E-14
H2	3112	6.888	0.0002101	-2.164E-07	1.376E-10	-2.452E-14
N2	3193	6.984	-0.0001687	5.128E-07	-1.948E-10	2.489E-14
H2O	-99150	7.959	0.0003182	3.576E-07	-1.074E-10	1.048E-14
CO	-45770	6.966	-9.373E-05	5.408E-07	-2.314E-10	3.306E-14
CO2	-165800	8.425	0.003167	-1.093E-06	2.497E-10	-2.7E-14
CH4	-25080	7.806	0.003597	5.746E-07	-4.709E-10	7.48E-14

The equation for the enthalpy of liquid water at temperature "t" is:

$$H \text{ Btu/lb mole} = -114,844 - 18.016 \times (212 - t)$$

4.2 Reforming and shift equilibrium

Reforming Reaction

Where initial mole flows or composition fractions are:

$$\begin{array}{ll} \text{H}_2 = \text{A} & \text{CO} = \text{D} \\ \text{H}_2\text{O} = \text{B} & \text{CO}_2 = \text{E} \\ \text{CH}_4 = \text{C} & x = \text{The CH}_4 \text{ converted} \end{array}$$

The equation for the reforming equilibrium constant is:

$$K_{pr} = \frac{(\text{PH}_2)^3 \times \text{PCO}}{\text{PCH}_4 \times \text{PH}_2\text{O}}$$

The reforming equilibrium constant is calculated from:

$$\text{Log}_{10}K_{pr} = 13.50732392 - 22297.20008 (V) + 972312.7798(V)^2$$

$$\text{Where } V = 1/ (T + 460)$$

$$T = \text{Exit temperature} - \text{delta } T \text{ (approach to equilibrium)}$$

$$\begin{aligned} \text{The total moles} &= (\text{C}-x) + (\text{B}-x+y) + (3x+\text{A}-y) + (\text{C}+x+y) + (\text{E}-y) \\ &= \text{A}+\text{B}+\text{C}+\text{D}+\text{E}+2x \end{aligned}$$

The 2x term reflects the fact that 2 extra moles are produced for each mole of CH₄ Which is converted to H₂. The partial pressure of a constituent is therefore:

$$\text{PH}_2 = \frac{\text{Pt} (3x + \text{A} - y)}{(\text{A}+\text{B}+\text{C}+\text{D}+\text{E}+2x)} \quad \text{example}$$

The equation for K_{pr} is therefore:

$$K_{pr} = \frac{(3x + \text{A} - y)^3 (\text{D} + x + y)}{(\text{C} - x) (\text{B} - x + y)} \times \frac{(\text{Pt})^2}{(\text{A} + \text{B} + \text{C} + \text{D} + \text{E} + 2x)^2}$$

where Pt = total pressure, atms

Shift Conversion

Where the shift equilibrium constant $K_{ps} = \frac{P_{H_2} \times P_{CO_2}}{P_{H_2O} \times P_{CO}}$

$$K_{ps} = \frac{(3x + A - y)(E - y)}{(B - x + y)(D + x + y)}$$

Solving this equation for y results in a quadratic equation

$$y = \frac{b^2 \pm (b^2 - 4ac)^{1/2}}{2a}$$

where $a = K_{ps} - 1$

$$b = K_{ps}(B + D) + E + A + 3x$$

$$c = K_{ps}(BD + Bx - Dx - x^2) - 3Ex - AE$$

The shift equilibrium constant as function of temperature is:

$$\text{Log}_{10}K_{ps} = -1.460864117 + 2492.498443(V) - 696866.2019(V)^2$$

$$V = 1 / (T + 460)$$

T = actual exit temperature, °F

The reform and shift equations are solved for x and y in the following way.

A CH₄ conversion fraction "x" is assumed. Then the shift fraction "y" is calculated from the quadratic shift equation. Based on the calculated "y" and assumed "x", a composition at the exit of the SHR is calculated. From this composition the reform constant is calculated and compared to the actual K_{pr} calculated at the SHR exit temperature. The model file then performs a dual iteration changing the assumed reform conversion fraction "x" until the proper K_{pr} is achieved, and adjusting the exit temperature to achieve an enthalpy balance.

4.3 Compressor

The compressor model for each compressor stage is based on an adiabatic compression of the inlet gas stream. The ideal energy for the adiabatic compression from Reference 4 is:

$$W_{ci} = wRT_{ci}(k/k-1)(P_o/P_i)^{((k/k-1)-1)}$$

Where W_{ci} = Ideal compressor work in Btu/hr

w = Flow, lb moles /hr

$R = 1544/778.3 = 1.984$ Btu/lb mole °R

T_{ci} = Inlet temperature in °R

k = Compressibility constant for the gas stream = c_p/c_v

P_o/P_i = Compressor pressure ratio

The actual work is determined by applying an adiabatic efficiency to the process

$$W_{c(actual)} = W_{ci}/\text{efficiency}$$

An energy balance around the compressor stage accounting for the heat loss determines the exit temperature from the compressor.

4.4 Turbine

The model for each turbine stage is based on an adiabatic expansion of the inlet gas stream. The ideal energy for the adiabatic expansion from Reference 4 is:

$$W_{ti} = wRT_{ti}(k/k-1)(P_o/P_i)^{((k/k-1)-1)}$$

Where W_{ti} = Ideal turbine work in Btu/hr

w = Flow, lb moles /hr

$R = 1544/778.3 = 1.984$ Btu/lb mole °R

T_{ti} = Inlet temperature in °R

k = Compressibility constant for the gas stream = c_p/c_v

P_o/P_i = Turbine expansion pressure ratio

The actual work output is determined by applying an adiabatic efficiency to the process

$$W_{t(actual)} = W_{ti} \times \text{efficiency}$$

An energy balance around the turbine stage accounting for the heat loss determines the exit temperature from the turbine.

An electrical efficiency for the turbine generator is applied to convert from rotational energy of the turbine to generator electrical output.

4.5 Burner

The method for determining the conditions at the exit of a burner is as follows. The composition of the streams entering a burner is determined by adding the flows. The temperature of the mixed stream before burning is determined by a temperature enthalpy iteration in which the mix temperature is changed until the enthalpy of the mix stream is balanced with the enthalpy of the combined inlet streams. After the mix temperature is determined, the conditions at the exit of the burner are determined as follows. The basic reactions for gases in a burner are:

From the above, the following equations are used to determine the composition of the gas at the exit of a burner where CO, CH₄ and H₂ conversion=100%.

1. $\text{CO}_{2\text{out}} = \text{CO}_{2\text{in}} + \text{CO}_{\text{in}} + \text{CH}_{4\text{in}}$
2. $\text{O}_{2\text{out}} = \text{O}_{2\text{in}} - 1/2\text{CO}_{\text{in}} - 2\text{CH}_{4\text{in}} - 1/2\text{H}_{2\text{in}}$
3. $\text{H}_2\text{O}_{\text{out}} = \text{H}_2\text{O}_{\text{in}} + \text{H}_{2\text{in}} + 2\text{CH}_{4\text{in}}$
4. $\text{CH}_{4\text{out}} = 0$
5. $\text{H}_{2\text{out}} = 0$
6. $\text{CO}_{\text{out}} = 0$
7. $\text{N}_{2\text{out}} = \text{N}_{2\text{in}}$

The temperature rise in the burner is determined by a temperature enthalpy iteration in which the exit temperature is changed until the enthalpy of the exit stream is balanced with the mix enthalpy before burning.

4.6 Heat exchangers

Heat exchanger performance is based on effectiveness "e" as defined in reference 1.

$$\begin{aligned} \text{where } e &= \text{WC}_{\text{ph}}(\text{Thi} - \text{Tho}) / \text{Wcp}_{\text{min}}(\text{Thi} - \text{Tci}) \\ &= \text{WC}_{\text{pc}}(\text{Tco} - \text{Tci}) / \text{Wcp}_{\text{min}}(\text{Thi} - \text{Tci}) \end{aligned}$$

In the heat exchanger model $C_p = (\text{Hin} - \text{Hout}) / (\text{Tin} - \text{Tout})$

Where H is the stream enthalpy in BTU/hr and T is the temperature in °F

4.7 Pressure losses

Pressure losses through the cell stack are representative of measured losses from operating cell stacks. Pressure losses through the burner, prereformer and heat exchangers are allocations for design based on previous more detailed design and construction experience. In some areas of the system the impact of pressure losses can be explored as deviations to a reference pressure loss.

4.8 Heat losses

The model includes provision at each energy balance point to include heat loss. Reference levels of heat loss are assigned for the cell stacks, based on an understanding of packaged cell stack designs, and for the gas turbine. Heat losses from other equipment are considered to be negligible relative to the magnitude of the stream energies.

4.9 Iteration technique for energy balances

The key iteration scheme used in the model is a mass and energy balance around a component. The exit temperature from the component is adjusted until an energy balance is established. This is accomplished using a logic scheme as shown in the following example from an EXCEL sheet.

	A	B	C	D	E	F	G	H	I	J	K
1	ENTHALPY IN, BTU/HR				-1.9800E+08			HEAT BALANCE			
2	ENTHALPY OUT, BTU/HR				-1.9800E+08			LOGIC FOR ITERAT	FALSE	FALSE	
3	HEAT LOSS, BTU/HR				0			ITERATION INCREM	0	0	
4	NET ENTHALPY, IN-OUT, BTU/HR				400			TEMP CHANGE=	0		

In cell E4 the net enthalpy is calculated from the in and out values.

Cell J2 has the logic: =AND (SIGN(E4)=1,E4>500), If E4 is greater than +500 the cell reads TRUE, if not, it reads FALSE.

Cell K2 has the logic: =AND(SIGN(E4)=-1,ABS(E4)>500), If E4 is negative and has an absolute value greater than 500, the cell reads TRUE, if not, it reads FALSE.

Cell J3 has the logic: =IF(J2=TRUE,J3+.01,J3), If J2 is true the value .01 is added to J3. If J2 is false J3 stays the same value.

Cell K3 has the logic: =IF(K2=TRUE,K3-.01,K3), If K2 is true the value .01 is subtracted from K3. If K2 is false K3 stays the same value.

Cell J4 has the logic: =J3+K3, This changing value is added to the temperature of the exit stream which changes its enthalpy.

The iteration proceeds with the temperature changing by 0.01°F until the net enthalpy is within 500 Btu/hr.

4.10 Cell stack

An MCFC has the following reactions at the electrodes.

The hydrogen consumed is based on Faraday's law as follows:

$$\text{WH}_2 = \frac{1.008 \text{ gm/gm eq} \times \text{lb} \times 3600 \text{ sec} \times 1000 \text{ watts} \times 1}{96,500 \text{ amp sec/ gm eq} \times 453.59 \text{ gm} \times \text{hr} \times \text{kilowatts} \times \text{volts/cell} \times 2.016 \text{ lb/lbmole}}$$

$$\text{WH}_2, \text{ lb moles /kW-hr} = \frac{0.04112}{\text{volts / cell}}$$

The energy (Heating Value) available follows the reaction

From reference 2 @ 1200 °F

$$11,530 + \frac{1}{2} (12,332) = -88714 + \text{Energy}$$

$$\text{Heating value Energy(HV)} = 106,410 \text{ BTU/ Lb mole H}_2 \text{ consumed}$$

The waste heat removed by the circulating anode and cathode gas streams

$$\text{Waste heat, Btu/hr} = \text{HV} \times \text{WH}_2 - 3413 \times \text{DC Power out, kW} - \text{heat loss}$$

The waste heat is removed by the endothermic reaction heat in the RUs and anodes, and by the enthalpy change of the anode and cathode streams

5. REFERENCES

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2. Girdler Catalyst Document 1954, Physical and Thermodynamic Properties of various Elements and Compounds and other useful Information.
3. DOE/METC-94 /1006 Fuel Cells A Handbook (Revision 4) November 1998
4. Elementary Thermodynamics by Virgil Moring Faires
5. Microsoft EXCEL Version 5 Users Guide
6. DOE report on high efficiency system

APPENDICES

hefplant.xlw sheets

1. Summary sheet
2. Boiler sheet
3. Prereformer sheet
4. Cell stack sheet
5. Compressor sheet
6. Air preheater sheet
7. Turbine sheet
8. Burner
9. Summary sheet for example case

APPENDIX 1

SUMMARY SHEET

hefplant.xls

SUMMARY

3/5/99 8:19		HIGH EFFICIENCY POWER PLANT PROCESS SUMMARY									
EXCEL 97 WORK BOOK PREPARED BY R.A.Sanderson P.E.											
FEBRUARY 1999				CASE	1						
		FIXED									
INPUT PARAMETERS		REFERENCE	+/- DEVIATION	OUTPUT CHARACTERISTICS				REQUIREMENT			
CH4 INPUT, MOLES/HR	=	296.00	0	NET AC POWER, KW				=	20,185	20,000	
PROCESS AIR FLOW, MOLES/HR	=	4870	0	NET AC LHV EFFICIENCY, %				=	70.29	> 70	
AMBIENT AIR TEMP F	=	59	0	PARASITIC LOSSES, KW				=	11		
WATER VAPOR PRESS, PSIA	=	0.147	0	GROSS AC POWER				=	20196		
FUEL LOWER HEATING VALUE, BTU/SCF	=	872.5	N/A	PLANT EXHAUST TEMP, F				=	222.0		
CELL STACK				FUEL CELLS							
CELL VOLTAGE	=	0.817	0	FUEL CELL AC OUTPUT, KW				=	17002		
CURRENT DENSITY, AMPS/M^2	=	0.12	0	FUEL CELL DC POWER, KW				=	17619		
NUMBER STACKS	=	70	N/A	FUEL UTILIZATION, %				=	78.0		
NUMBER CELLS/STACK	=	330	N/A	CATHODE EXIT TEMP, DEG F				=	1179.4	1180 MAX	
CELL AREA, M^2	=	7.8	N/A	CATHODE INLET TEMP, DEG F				=	1045.5	1030 MIN	
ANODE EXIT TEMP DEG C	=	1170	0	FUEL CELL OXYGEN UTILIZATION, %				=	50.2		
METHANE CONVERSION, %	=	100	N/A	FUEL CELL INLET O2 FRACTION				=	0.1273		
STACK HEAT LOSS, MBTU/HR	=	700,000	0	OUTLET O2 FRACTION				=	0.0784		
INVERTER EFFICIENCY, %	=	96.5	0	FUEL CELL INLET CO2 FRACTION				=	0.1717		
PARASITIC PWR, CONTROLS&MISC, KW	=	10	0	OUTLET CO2 FRACTION				=	0.0543		
FUEL PROCESSING	=			GAS TURBINE							
PREREFORM PRES, PSIA	=	18	0	TURBINE GEN NETPOWER AC, KW				=	3194		
PREREFORM INLET TEMP, C	=	752	E-3 EXIT	HI TURBINE INLET TEMPERATURE, F				=	1526		
STEAM/CH4 RATIO	=	1.5	0	LOW TURBINE INLET TEMPERATURE, F				=	1220		
INTERNAL REFORM TEMP, C	=	1075	0	HIGH TURBINE POWER, KW				=	8038		
GAS TURBINE			0	LOW TURBINE POWER, KW				=	1154		
GAS TURBINE COMP EFF, %	=	83	0	1ST STAGE COMPRESSOR WORK, KW				=	1825		
GAS TURBINE TURB EFF, %	=	83	0	2ND STAGE COMPRESSOR WORK, KW				=	2052		
GT COMPRESSOR PRESS RATIOS	=	2.47	0	3RD STAGE COMPRESSOR WORK, KW				=	2055		
EACH INTERCOOLER PRESS LOSS, PSI	=	1	0								
PRESSURE LOSS, COMP OUT TO TURB IN, PSI	=	4	0								
PRESSURE LOSS, E-9, PSI	=	1	0	PROCESS WATER TOTAL, GAL/MIN				=	16.0		
1ST TURBINE STAGE OUTLET PRESSURE, PSIA	=	22	0								
GENERATOR EFFICIENCY, %	=	98	0								
TURBINE STAGE HEAT LOSS, BTU/HR	=	10000	0								
HEAT EXCHANGER SUMMARY		REFERENCE	+/- DEVIATION	REQUIRED HEAT EXCHANGER EFFECTIVENESS							
E-1 SECOND STAGE AIR HEATER	COLD SIDE EXIT	1058	0	E-1				=	0.87		
E-2 PROCESSED FUEL REHEATER	COLD SIDE EXIT	932	0	E-2				=	0.86		
E-3 FUEL /STEAM HEATER	COLD SIDE EXIT	752	0	E-3				=	0.75		
E-4 FIRST STAGE AIR HEATER	COLD SIDE EXIT	816	0	E-4				=	0.94		
E-5 BOILER	COLD SIDE EXIT	239	0	E-5				=	0.77		
E-6 NATURAL GAS HEATER	COLD SIDE EXIT	212	0	E-6				=	0.76		
E-7 FEEDWATER HEATER	COLD SIDE EXIT	203	0	E-7				=	0.75		
E-8 TURBINE INLET HEATER	COLD SIDE EXIT	1526	0	E-8				=	0.90		
E-9 TURBINE INLET REHEATER	COLD SIDE EXIT	1220	0	E-9				=	0.84		
E-10 INTERCOOLER	EFFECTIVENES	0.762	0								
E-11 INTERCOOLER	EFFECTIVENES	0.847	0								
E-12 COOLING TOWER	EFFECTIVENES	0.811	0								

SUMMARY

HIGH EFFICIENCY POWER PLANT PROCESS SUMMARY													
PROCESS CONDITIONS													
STATION		TEMP	PRESS	ENTHALPY	CASE				COMPOSITION, VOLUME FRACTION				FLOW
NO	DESCRIPTION	DEG F	PSIA	BTU/HR	H2	H2O	CH4	CO	CO2	O2	N2	MOLES/HR	LBS/HR
1	NATURAL GAS IN	59.0	29.70	-7,949,462	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
2	DESULFUR NAT GAS	15.0	24.70	-7,949,462	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
3	HEATED NAT GAS	212.0	24.60	-7,551,780	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
4	FUEL/STEAM/RECYCLE	233.7	19.20	-51,454,714	0.0012	0.5991	0.3835	0.0000	0.0083	0.0000	0.0080	752.02	13,187
5	PREREFORMER INLET	752.0	19.00	-47,683,213	0.0012	0.5991	0.3835	0.0000	0.0083	0.0000	0.0080	752.02	13,187
6	PREREFORMER EXIT	611.3	17.00	-47,682,947	0.0748	0.5448	0.3539	0.0001	0.0264	0.0000	0.0078	774.58	13,187
7	FUEL/STEAM TO E-2	611.3	16.71	-46,948,630	0.0742	0.5406	0.3511	0.0001	0.0262	0.0000	0.0077	768.57	12,984
8	FUEL/STEAM FROM E-2	932.0	16.61	-44,362,077	0.0742	0.5406	0.3511	0.0001	0.0262	0.0000	0.0077	768.57	12,984
9	FUEL TO STACK Rus	932.0	16.60	-44,362,077	0.0746	0.5357	0.3555	0.0001	0.0264	0.0000	0.0078	768.57	12,984
10	FUEL FROM Rus	1075.0	15.60	-31,993,635	0.4876	0.2223	0.1411	0.0619	0.0812	0.0000	0.0058	1020.34	12,984
11	FUEL TO ANODES	1075.0	15.60	-31,993,635	0.4876	0.2223	0.1411	0.0619	0.0812	0.0000	0.0058	1020.34	12,984
12	FUEL FROM ANODES	1170.0	15.52	-243,537,416	0.0715	0.3897	0.0000	0.0423	0.4938	0.0000	0.0027	2195.09	66,199
13	FUEL TO BURNER	1170.0	15.50	-243,537,416	0.0715	0.3897	0.0000	0.0423	0.4938	0.0000	0.0027	2195.09	66,199
14	BURNER PREMIX	1137.1	15.45	-195,731,211	0.0222	0.1280	0.0000	0.0132	0.1555	0.1427	0.5385	7065.09	206,400
15	BURNER EXHAUST	1580.3	15.35	-195,731,287	0.0000	0.1529	0.0000	0.0000	0.1717	0.1273	0.5482	6940.15	206,400
16	EXHAUST FROM E-8	1297.1	15.27	-213,786,682	0.0000	0.1529	0.0000	0.0000	0.1717	0.1273	0.5482	6940.15	206,400
17	CATHODE INLET	1045.5	15.19	-229,327,392	0.0000	0.1529	0.0000	0.0000	0.1717	0.1273	0.5482	6940.15	206,400
18	CATHODE EXHAUST	1179.4	15.11	-90,986,104	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
19	EXHAUST TO E-1	1179.4	15.15	-90,986,104	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
20	EXHAUST TO E-2	985.6	15.05	-99,963,142	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
21	EXHAUST TO E-3	928.9	15.00	-102,549,695	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
22	EXHAUST TO E-4	845.2	14.95	-106,321,196	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
23	EXHAUST TO E-5	447.9	14.85	-123,640,226	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
24	EXHAUST TO E-6	259.5	14.80	-131,535,186	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
25	EXHAUST TO E-7	249.9	14.75	-131,932,867	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
26	EXHAUST FROM SYSTEM	222.0	14.70	-133,084,674	0.0000	0.1891	0.0000	0.0000	0.0543	0.0784	0.6782	5609.99	153,185
27	PROCESS AIR IN	59.0	14.70	10,101,093	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
28	1ST STAGE COMP IN	59.0	14.60	10,101,093	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
29	1ST STAGE COMP OUT	241.6	36.06	16,331,515	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
30	2ND STAGE COMP IN	123.4	35.06	12,292,272	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
31	2ND STAGE COMP OUT	327.7	86.60	19,297,089	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
32	3RD STAGE COMP IN	123.4	85.60	12,292,214	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
33	3RD STAGE COMP OUT	328.0	211.44	19,305,176	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
34	PREHEATER E-4 OUT	816.0	210.11	36,624,206	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
35	PREHEATER E-1 OUT	1058.0	208.77	45,601,244	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
36	1ST TURBINE IN	1526.0	207.44	63,656,640	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
37	1ST TURBINE OUT	804.8	22.00	36,213,725	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
38	2ND TURBINE IN	1220.0	21.00	51,754,434	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201
39	2ND TURBINE OUT	1116.4	15.50	47,806,344	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,870.00	140,201

SUMMARY

HIGH EFFICIENCY POWER PLANT PROCESS SUMMARY													
PROCESS CONDITIONS													
CASE 1													
STATION		TEMP	PRESS	ENTHALPY	COMPOSITION, VOLUME FRACTION							FLOW	FLOW
NO	DESCRIPTION	DEG F	PSIA	BTU/HR	H2	H2O	CH4	CO	CO2	O2	N2	MOLES/HR	LBS/HR
40	PROCESS WATER IN	59.0	30	-52,214,531	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
41	TREATED WATER	59.0	24	-52,214,531	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
42	FEEDWATER HTR OUT	203.0	23	-51,062,724	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
43	STEAM FROM BOILER	239.0	22	-43,167,937	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
44	STEAM TO EJECTOR	239.0	21.5	-43,167,937	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	444.00	7,999
45	FUEL RECYCLE	611.3	17	-734,257	0.0742	0.5407	0.3512	0.0000	0.0262	0.0000	0.0077	12.02	203
46	STEAM/ RECYCLE MIX	250.0	19.5	-43,902,543	0.0020	0.9879	0.0093	0.0000	0.0007	0.0000	0.0002	456.02	8,202
47	COOLING PMP INLET	86.5	29	-608,948,479	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5200.00	93,683
48	COOLING PMP EXIT	86.5	36	-608,948,479	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5,200.00	93,683
49	COOLANT TO E-10	86.5	36	-234,210,953	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2000.00	36,032
50	COOLANT FROM E-10	198.6	34	-230,171,711	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	2000.00	36,032
51	COOLANT TO E-11	86.5	36	-374,737,525	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3200.00	57,651
52	COOLANT FROM E-11	208.0	34	-367,732,651	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	3200.00	57,651
53	COOLANT TO E-12	204.4	34	-597,904,071	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	5200.00	93,683
54	AIR TO TOWER	59.0	14.7	31,112,195	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	14999.99	431,830
55	AIR FROM TOWER	164.3	14.7	42,156,603	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	14999.99	431,830
HEAT & MASS BALANCE AROUND THE ENTIRE PLANT													
SYSTEM ENERGY AND MOLE BALANCE													
STATION		ENERGY		MASS, LB/HR		MOLES							
		BTU/HR				H2	O2	C	N2				
IN	FUEL IN	1	-7,949,462	4,985		568.3	5.9	290.1	5.9				
	PROCESS AIR IN	27	10,101,093	140,201		48.7	1047.0	14.6	3798.6				
	WATER IN	40	-52,214,531	7,999		444.0	222.0	0.0	0.0				
	COOLING AIR IN	54	31,112,195	431,830		150.0	3225.0	45.0	11700.0				
	TOTAL		-18,950,705	585,014		1211.0	4499.9	349.7	15504.5				
OUT	FUEL CELL DC POWER		60,133,647										
	EXHAUST	26	-133,084,674	153,185		1061.0	1275.0	304.7	3804.5				
	COOLING AIR OUT	55	42,156,603	431,830		150.0	3225.0	45.0	11700.0				
	GT POWER		11,123,206			1211.0	4499.9	349.7	15504.5				
	GT HEAT LOSS		20,000										
	STACK HEAT LOSS		700,000										
	TOTAL		-18,951,219	585,014									
	ERROR (IN-OUT)		514	0		0.0	0.0	0.0	0.0				
	(IN-OUT)/IN, %		0.0027										

APPENDIX 2

BOILER SHEET

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BOILER

3/3/99 14:19		BOILER BOILER FEEDWATER HEATER & FUEL PREHEATER									

BOILER

FUEL PREHEATER E-6										
STATION	24	TEMP, F	259	126.4	DEG C	FUEL FLOW LBMOLES/HR =				
HOT SIDE INLET										296
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	27.306
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678	1.000
SPEC ENTH, BTU/LB MOLE			4,910	-97,058	-22,804	-43,960	-163,419	5,019	5,002	
ENTHALPY, BTU/HR			0	-102,980,143	0	0	-49,791,580	2,207,175	19,029,777	-131,534,771
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587	153,185
STATION	25	TEMP, F	249.9	121.0	DEG C					
HOT SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	27.306
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678	1.000
SPEC ENTH, BTU/LB MOLE			4,843	-97,136	-22,898	-44,028	-163,513	4,950	4,935	
ENTHALPY, BTU/HR			0	-103,063,501	0	0	-49,820,366	2,176,772	18,774,642	-131,932,453
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587	153,185
STATION	2	TEMP, F	59.0	15.0	DEG C					
COLD SIDE INLET (FUEL IN)										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	16.841
MOLE FLOW, LB MOLES/HR			0.00	0.00	284.16	0.00	5.92	0.00	5.92	296.00
MOLE FRACTION			0.000	0.000	0.960	0.000	0.020	0.000	0.020	1.000
SPEC ENTH, BTU/LB MOLE			3,519	-98,679	-24,607	-45,359	-165,292	3,600	3,605	
ENTHALPY, BTU/HR			0	0	-6,992,272	0	-978,529	0	21,339	-7,949,462
MASS FLOW LB/HR			0	0	4,558	0	261	0	166	4,985
STATION	3	TEMP, F	212.0	100.0	DEG C					
COLD SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	16.841
MOLE FLOW, LB MOLES/HR			0.00	0.00	284.16	0.00	5.92	0.00	5.92	296.00
MOLE FRACTION			0.000	0.000	0.960	0.000	0.020	0.000	0.020	1.000
SPEC ENTH, BTU/LB MOLE			4,580	-97,445	-23,259	-44,293	-163,881	4,678	4,671	
ENTHALPY, BTU/HR			0	0	-6,609,252	0	-970,178	0	27,650	-7,551,780
MASS FLOW LB/HR			0	0	4,558	0	261	0	166	4,985
STATION		STATION		STATION	ASSUMED EFFECTIVENESS, e =		0.763			
Thi, F	=	24	259	25	CALCULATED Tho F =		249.9	=Thi-eCmin/Ch(Thi-Tci)		
Tci, F	=	2	59.0	3	SELECTED COLD SIDE EXIT		212.0			
Ch=DH/DT	=	BTU/HR F	41425		ENERGY BALANCE	IN	OUT	DELTA		
Cc=DH/DT	=	BTU/HR F	2599		HOT SIDE	-131,534,771	-131,932,453	397,682		
Cmin	=	BTU/HR F	2599		COLD SIDE	-7,949,462	-7,551,780	-397,682		
Thi-Tci, F	=		200		TOTAL	-139,484,233	-139,484,233	0		
Cmin/Cmax	=		0.06							
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/Cmin(Thi-Tci)		0.763			

BOILER

FEEDWATER HEATER E-7										
STATION	25	TEMP, F	250	121.0	DEG C	WATER /FUEL RATIO				1.5
HOT SIDE INLET						PROCESS WATER FLOW, LB MOLES /HR				444
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	27.306
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678	1.000
SPEC ENTH, BTU/LB MOLE			4,843	-97,136	-22,898	-44,028	-163,513	4,950	4,935	
ENTHALPY, BTU/HR			0	-103,063,501	0	0	-49,820,366	2,176,772	18,774,842	-131,932,453
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587	153,185
STATION	26	TEMP, F	222.0	105.6	DEG C	PLANT EXHAUST				
HOT SIDE EXIT										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	27.306
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678	1.000
SPEC ENTH, BTU/LB MOLE			4,650	-97,364	-23,165	-44,223	-163,785	4,750	4,740	
ENTHALPY, BTU/HR			0	-103,304,801	0	0	-49,903,121	2,088,846	18,034,815	-133,084,260
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587	153,185
STATION	41	TEMP, F	59.0	15.0	DEG C					
COLD SIDE INLET										
	GAS		H2	H2O(LIQUID)	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	18.016
MOLE FLOW, LB MOLES/HR			0.00	444.00	0.00	0.00	0.00	0.00	0.00	444.00
MOLE FRACTION			0.000	1.000	0.000	0.000	0.000	0.000	0.000	1.000
SPEC ENTH, BTU/LB MOLE			3,519	-52,214,531	-24,607	-45,359	-165,292	3,600	3,605	
ENTHALPY, BTU/HR			0	-52,214,531	0	0	0	0	0	-52,214,531
MASS FLOW LB/HR			0	7,999	0	0	0	0	0	7,999
STATION	42	TEMP, F	203.0	95.0	DEG C					
COLD SIDE EXIT										
	GAS		H2	H2O(LIQUID)	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	18.016
MOLE FLOW, LB MOLES/HR			0.00	444.00	0.00	0.00	0.00	0.00	0.00	444.00
MOLE FRACTION			0.000	1.000	0.000	0.000	0.000	0.000	0.000	1.000
SPEC ENTH, BTU/LB MOLE			4,517	-51,062,724	-23,343	-44,356	-163,968	4,614	4,608	
ENTHALPY, BTU/HR			0	-51,062,724	0	0	0	0	0	-51,062,724
MASS FLOW LB/HR			0	7,999	0	0	0	0	0	7,999
		STATION		STATION	ASSUMED EFFECTIVENESS, e =			0.754		
Thi, F	=	25	250	26	CALCULATED Tho F =			222.0	=Thi-eCmin/Ch(Thi-Tci)	
Tci, F	=	41	59	42	SELECTED COLD SIDE EXIT			203.0		
Ch=DH/DT	=	BTU/HR F	41345		ENERGY BALANCE				IN	OUT
Cc=DH/DT	=	BTU/HR F	7999		HOT SIDE			-131,932,453	-133,084,260	1,151,807
Cmin	=	BTU/HR F	7999		COLD SIDE			-52,214,531	-51,062,724	-1,151,807
Thi-Tci, F	=		191		TOTAL			-184,146,984	-184,146,984	0
Cmin/Cmax	=		0.19							
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/Cmin(Thi-Tci)			0.754		

APPENDIX 3

PREREFORMER SHEET

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3/3/99 14:19												
PRERFORMER												
FUEL/STEAM/RECYCLE MIX, E-3, PRERFORMER, E-2												
STATION	3	TEMP, F	212.0	100.0	DEG C							
FUEL FROM FUEL PREHEATER E-6												
			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL		
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	18.841		
MOLE FLOW, LB MOLES/HR			0.00	0.00	284.16	0.00	5.92	0.00	5.92	296.00		
MOLE FRACTION			0.000	0.000	0.960	0.000	0.020	0.000	0.000	1.000		
SPEC ENTH, BTU/LB MOLE			4,580	-97,445	-23,259	-44,293	-163,881	4,678	4,671			
ENTHALPY, BTU/HR			0	0	-6,609,252	0	-970,178	0	27,650	-7,551,780		
MASS FLOW LB/HR			0	0	4,558	0	261	0	166	4,985		
STEAM FROM BOILER												
STATION	43	TEMP, F	239.0	115.0	DEG C							
GAS												
			H2	H2O(VAPOR)	CH4	CO	CO2	O2	N2	TOTAL		
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	18.016		
MOLE FLOW, LB MOLES/HR			0.000	444.000	0.000	0.000	0.000	0.000	0.000	444		
MOLE FRACTION			0.000	1.000	0.000	0.000	0.000	0.000	0.000	1.000		
SPEC ENTH, BTU/LB MOLE			4,768	-97,225	-23,003	-44,104	-163,620	4,872	4,859			
ENTHALPY, BTU/HR			0	-43,167,937	0	0	0	0	0	-43,167,937		
MASS FLOW LB/HR			0	7,999	0	0	0	0	0	7,999		
RECYCLE FROM PRERFORMER												
RECYCLE FRACTION												
0.0154												
STATION	45	TEMP, F	611.3	321.9	DEG C							
RECYCLE FROM PRERFORMER EXIT												
			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL		
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	16.892		
MOLE FLOW, LB MOLES/HR			0.892	6.499	4.221	0.000	0.315	0.000	0.093	12.020		
MOLE FRACTION			0.074	0.541	0.351	0.000	0.026	0.000	0.008	1.000		
SPEC ENTH, BTU/LB MOLE			7,369	-94,098	-18,892	-41,452	-159,683	7,635	7,492			
ENTHALPY, BTU/HR			6,576	-611,552	-79,743	0	-50,232	0	694	-734,257		
MASS FLOW LB/HR			2	117	68	0	14	0	3	203		
RECYCLE FROM PRERFORMER												
RECYCLE FRACTION												
0.0154												
STATION	46	TEMP, F	250.0	121.1	DEG C							
RECYCLE/STEAM MIX												
			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL		
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	17.986		
MOLE FLOW, LB MOLES/HR			0.892	450.499	4.221	0.000	0.315	0.000	0.093	456.020		
MOLE FRACTION			0.002	0.988	0.009	0.000	0.001	0.000	0.000	1.000		
SPEC ENTH, BTU/LB MOLE			4,844	-97,135	-22,896	-44,027	-163,512	4,951	4,936			
ENTHALPY, BTU/HR			4,323	-43,759,240	-96,646	0	-51,437	0	457	-43,902,543		
MASS FLOW LB/HR			2	8,116	68	0	14	0	3	8,202		

PREREFORMER

ENTHALPY IN, BTU/HR	44+45		-4.390E+07			HEAT BALANCE				
ENTHALPY OUT, BTU/HR			-4.390E+07			LOGIC FOR ITERATION	FALSE	FALSE		
HEAT LOSS, BTU/HR			0			ITERATION INCREMENT	21.62	-21.6		
NET ENTHALPY, IN - OUT, BTU/HR			349			TEMP CHANGE =	0.02			
STATION	4	TEMP, F	233.7	112.1	DEG C					
FUEL/STEAM/RECYCLE MIX										
GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT		2.016	18.016	16.042	28.01	44.01	32	28.016	17.535	
MOLE FLOW, LB MOLES/HR		0.8924	450.4991	288.3811	0.0000	6.2346	0.0000	6.0126	752.020	
MOLE FRACTION		0.001	0.599	0.383	0.000	0.008	0.000	0.008	1.000	
SPEC ENTH, BTU/LB MOLE		4,731	-97,268	-23,053	-44,141	-163,671	4,834	4,822		
ENTHALPY, BTU/HR		4,222	-43,819,342	-6,648,163	0	-1,020,422	0	28,992	-51,454,714	
MASS FLOW LB/HR		2	8,116	4,626	0	274	0	168	13,187	
ENTHALPY IN, BTU/HR	46+3		-5.145E+07			HEAT BALANCE				
ENTHALPY OUT, BTU/HR			-5.145E+07			LOGIC FOR ITERATION	FALSE	FALSE		
HEAT LOSS, BTU/HR			0			ITERATION INCREMENT	26.05	-20.36		
NET ENTHALPY, IN - OUT, BTU/HR			391			TEMP CHANGE =	5.69			
PREREFORMER INLET HEATER, E-3										
STATION	21	TEMP, F	929	498.3	DEG C					
HOT SIDE INLET										
GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT		2.016	18.016	16.042	28.01	44.01	32	28.016	27.306	
MOLE FLOW, LB MOLES/HR		0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99	
MOLE FRACTION		0.000	0.189	0	0.000	0.054	0.078	0.678	1.000	
SPEC ENTH, BTU/LB MOLE		9,603	-91,269	-14,564	-39,096	-155,951	10,125	9,818		
ENTHALPY, BTU/HR		0	-96,837,940	0	0	-47,516,125	4,452,733	37,352,106	-102,549,225	
MASS FLOW LB/HR		0	19,115	0	0	13,409	14,073	106,587	153,185	
STATION	22	TEMP, F	845	451.8	DEG C					
HOT SIDE EXIT										
GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT		2.016	18.016	16.042	28.01	44.01	32	28.016	27.306	
MOLE FLOW, LB MOLES/HR		0	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99	
MOLE FRACTION		0.000	0.189	0	0.000	0.054	0.078	0.678	1.000	
SPEC ENTH, BTU/LB MOLE		9,013	-92,030	-15,773	-39,726	-156,960	9,459	9,197		
ENTHALPY, BTU/HR		0	-97,645,380	0	0	-47,823,817	4,159,697	34,988,772	-106,320,727	
MASS FLOW LB/HR		0	19,115	0	0	13,409	14,073	106,587	153,185	

PREREFORMER

STATION	4	TEMP, F	233.69	112.1	DEG C					
COLD SIDE INLET										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	17.535
MOLE FLOW, LB MOLES/HR			0.89	450.50	288.38	0.00	6.23	0.00	6.01	752.02
MOLE FRACTION			0.001	0.599	0.383	0.000	0.008	0.000	0.008	1.000
SPEC ENTH, BTU/LB MOLE			4,731	-97,268	-23,053	-44,141	-163,671	4,834	4,822	
ENTHALPY, BTU/HR			4,222	-43,819,342	-6,648,163	0	-1,020,422	0	28,992	-51,454,714
MASS FLOW LB/HR			2	8,116	4,626	0	274	0	168	13,187
STATION	5	TEMP, F	752.00	400.0	DEG C					
COLD SIDE EXIT										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	17.535
MOLE FLOW, LB MOLES/HR			0.89	450.50	288.38	0.00	6.23	0.00	6.01	752.02
MOLE FRACTION			0.001	0.599	0.383	0.000	0.008	0.000	0.008	1.000
SPEC ENTH, BTU/LB MOLE			8,357	-92,865	-17,064	-40,421	-158,065	8,725	8,511	
ENTHALPY, BTU/HR			7,457	-41,835,438	-4,920,940	0	-985,468	0	51,175	-47,683,213
MASS FLOW LB/HR			2	8,116	4,626	0	274	0	168	13,187
Thi, F	=	STATION 21	929	22	ASSUMED EFFECTIVENESS, e =		0.746			
Tci, F	=	4	234	5	CALCULATED Tho F =		845.2			=Thi-eCmin/Ch(Thi-Tci)
Ch=DH/DT	=	BTU/HR F	45101.02		CALCULATED Tco F		752.0			=Tci+eCmin/Cc(Thi-Tci)
Cc=DH/DT	=	BTU/HR F	7276.54		ENERGY BALANCE	IN	OUT	DELTA		
Cmin	=	BTU/HR F	7276.54		HOT SIDE	-102,549,225	-106,320,727	3,771,501		
Thi-Tci, F	=		695		COLD SIDE	-51,454,714	-47,683,213	-3,771,501		
Cmin/Cmax	=		0.16		TOTAL	-154003940	-154003940	0		
CALCULATED EFFECTIVENESS FOR SELECTED Tco										
					e = Cc(Tco-Tci)/Cmin(Thi-Tci)		0.746			
PREREFORMER										
STATION	5	TEMP, F	752.0	400.0	DEG C	PRESSURE, ATM =	1.156	17 PSIA		
PREREFORMER INLET										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	17.535
MOLE FLOW, LB MOLES/HR			0.89	450.50	288.38	0.00	6.23	0.00	6.01	752.02
MOLE FRACTION			0.001187	0.599052	0.383475	0.000000	0.008290	0.000000	0.007995	1.000
SPEC ENTH, BTU/LB MOLE			8,357	-92,865	-17,064	-40,421	-158,065	8,725	8,511	
ENTHALPY, BTU/HR			7,457	-41,835,438	-4,920,940	0	-985,468	0	51,175	-47,683,213
MASS FLOW LB/HR			2	8,116	4,626	0	274	0	168	13,187
SHIFT EQUILIBRIUM CONSTANT										
TEMP, DEG F		611.34	REFORM EQUILIBRIUM CONSTANT			TEMP, DEG F =	611.34	APPROACH TEMP	0	
TEMP, DEG R		1071.34				TEMP, DEG R =	1071.34			
V=1/Tr =		0.00093341				V=1/Tr =	0.00093341			
log10 Kp=		1.472808358				Log10 Kp =	-6.45798413			
Kp=		29.7036				Kp =	3.48350E-07			

PREREFORMER

BACK SHIFT CONVERSION FRACTION = y				REFORM CONVERSION FRACTION = X					
a =	28.7035501			ASSUME VALUE X =	0.01900		1+2x=	1.0300	
b =	17.860			CALCULATED FRACTIONS					
c =	0.326846952			H2	H2O	CH4	CO	CO2	
y =	-0.018872439			0.07705	0.56118	0.36448	0.00013	0.02716	1.0300
CALCULATED CONVERSION CONSTANT Kp				CALCULATE Kp =		3.48318E-07			
				Kp ACT-Kp(X) =		3.40178E-11			
				ITERATION FOR CLOSURE ON X					
					LOGIC FOR ITERATION		FALSE	FALSE	
					ITERATION INCREMENT		0.013308	-0.01431	
					REVISED VALUE X =		-1.00E-03		
				CH4 CONVERTED IN RU, LB MOLES / HR			14.2869		
				CH4 CONVERSION =			0.0495		
STATION	6	TEMP, F	611.3	321.9	DEG C				
PREREFORMER EXIT									
	GAS		H2	H2O	CH4	CO	CO2	O2	N2
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016
MOLE FLOW, LB MOLES/HR			57.945	422.020	274.094	0.094	20.427	0.000	6.013
MOLE FRACTION			0.075	0.545	0.354	0.000	0.026	0.000	0.008
SPEC ENTH, BTU/LB MOLE			7,369	-94,098	-18,892	-41,452	-159,683	7,635	7,492
ENTHALPY, BTU/HR			427,006	-39,711,144	-5,178,092	-3,914	-3,261,848	0	45,044
MASS FLOW LB/HR			117	7,603	4,397	3	899	0	168
ENTHALPY IN, BTU/HR				-4.7683E+07			HEAT BALANCE		
ENTHALPY OUT, BTU/HR				-4.7683E+07			LOGIC FOR ITERATION		FALSE
HEAT LOSS, BTU/HR				0			ITERATION INCREMENT		134.73
NET ENTHALPY, IN - OUT, BTU/HR				-266			TEMP CHANGE =		-2.06
PREREFORMER EXIT RECYCLE TO RECYCLE EJECTOR									
RECYCLE FRACTION =		0.0154							
FRACTION TO E-2		0.9846							
PREREFORMER EXIT HEATER, E-2									
STATION	20	TEMP, F	986	529.8	DEG C				
HOT SIDE INLET									
	GAS		H2	H2O	CH4	CO	CO2	O2	N2
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678
SPEC ENTH, BTU/LB MOLE			10,005	-90,745	-13,716	-38,665	-155,255	10,582	10,243
ENTHALPY, BTU/HR			0	-96,282,521	0	0	-47,304,245	4,653,457	38,970,636
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587

PREREFORMER

STATION	21	TEMP, F	929	498.3	DEG C					
HOT SIDE EXIT										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	27.306
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678	1.000
SPEC ENTH, BTU/LB MOLE			9,603	-91,269	-14,564	-39,096	-155,951	10,125	9,818	
ENTHALPY, BTU/HR			0	-96,837,940	0	0	-47,516,125	4,452,733	37,352,106	-102,549,225
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587	153,185
STATION	7	TEMP, F	611.34	321.9	DEG C					
COLD SIDE INLET										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	16.894
MOLE FLOW, LB MOLES/HR			57.05	415.52	269.87	0.09	20.11	0.00	5.92	768.57
MOLE FRACTION			0.074	0.541	0.351	0.000	0.026	0.000	0.008	1.000
SPEC ENTH, BTU/LB MOLE			7,369	-94,098	-18,892	-41,452	-159,683	7,635	7,492	
ENTHALPY, BTU/HR			420,431	-39,099,592	-5,098,349	-3,854	-3,211,616	0	44,350	-46,948,630
MASS FLOW LB/HR			115	7,486	4,329	3	885	0	166	12,984
STATION	8	TEMP, F	932.00	500.0	DEG C					
COLD SIDE EXIT										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	16.894
MOLE FLOW, LB MOLES/HR			57.05	415.52	269.87	0.09	20.11	0.00	5.92	768.57
MOLE FRACTION			0.074	0.541	0.351	0.000	0.026	0.000	0.008	1.000
SPEC ENTH, BTU/LB MOLE			9,626	-91,240	-14,518	-39,073	-155,912	10,150	9,841	
ENTHALPY, BTU/HR			549,164	-37,912,100	-3,917,989	-3,633	-3,135,780	0	58,260	-44,362,077
MASS FLOW LB/HR			115	7,486	4,329	3	885	0	166	12,984
		STATION	STATION	ASSUMED EFFECTIVENESS, e =				0.857		
Thi, F	=	20	986	21	CALCULATED Tho F =				928.9	=Thi-eCmin/Ch(Thi-Tci)
Tci, F	=	7	611	8	CALCULATED Tco F				932.0	=Tci+eCmin/Cc(Thi-Tci)
Ch=DH/DT	=	BTU/HR F	45549.35		ENERGY BALANCE		IN	OUT	DELTA	
Cc=DH/DT	=	BTU/HR F	8066.34		HOT SIDE		-99,962,673	-102,549,225	2,586,553	
Cmin	=	BTU/HR F	8066.34		COLD SIDE		-46,948,630	-44,362,077	-2,586,553	
Thi-Tci, F	=		374		TOTAL		-146,911,303	-146,911,303	0	
Cmin/Cmax	=		0.18							
CALCULATED EFFECTIVENESS FOR SELECTED Tco				e = Cc(Tco-Tci)/Cmin(Thi-Tci)				0.857		

APPENDIX 4

CELL STACK SHEET

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3/3/99 14:19		CELL STACK (INCLUDES INTERNAL REFORMER UNITS)									
STATION	9	TEMP, F	932.0	500.0	DEG C		PRESSURE, ATM =	1.041			
RU INLET = E-2 EXIT(8)							ATM^2 =	1.083			
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	16.894	
MOLE FLOW, LB MOLES/HR			57.05	415.52	269.87	0.09	20.11	0.00	5.92	768.57	
MOLE FRACTION			0.0742	0.5406	0.3511	0.0001	0.0262	0.0000	0.0077	1.000	
SPEC ENTH, BTU/LB MOLE			9,626	-91,240	-14,518	-39,073	-155,912	10,150	9,841		
ENTHALPY, BTU/HR			549,164	-37,912,100	-3,917,989	-3,633	-3,135,780	0	58,260	-44,362,077	
MASS FLOW LB/HR			115	7,486	4,329	3	885	0	166	12,984	
SHIFT EQUILIBRIUM CONSTANT					REFORM EQUILIBRIUM CONSTANT						
TEMP, DEG F		1075			TEMP, DEG F =	1075	APPROACH TEMP			0	
TEMP, DEG R		1535			TEMP, DEG R =	1535					
V=1/Tr =		0.000651			V=1/Tr =	0.000651466					
log10 Kp=		0.458669			Log10 Kp =	-0.605882307					
Kp=		2.8752			Kp =	0.24781					
BACK SHIFT CONVERSION FRACTION = y					REFORM CONVERSION FRACTION = X						
a =	1.875205				ASSUME VALUE X =	0.16379		1+2x=		1.3276	
b =	2.147				CALCULATED FRACTIONS						
c =	0.1628				H2	H2O	CH4	CO	CO2		
y =	-0.08167					0.64727	0.29518	0.18735	0.08224	0.10784	1.3199
CALCULATED CONVERSION CONSTANT Kp					CALCULATE Kp =	0.247884406					
					Kp ACT-Kp(X) =	-7.5054E-05					
					ITERATION FOR CLOSURE ON X						
								LOGIC FOR ITERATION	FALSE	FALSE	
								ITERATION INCREMENT	0.03927	-0.07548	
								REVISED VALUE X =	0.16379		
					CH4 CONVERTED IN RU, LB MOLES / HR				125.8845		
					CH4 CONVERSION =				0.4665		
STATION	10	TEMP, F	1075.0	579.4	DEG C						
RU OUT											
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	12.725	
MOLE FLOW, LB MOLES/HR			497.47	226.87	143.99	63.21	82.88	0.00	5.92	1020.34	
MOLE FRACTION			0.488	0.222	0.141	0.062	0.081	0.000	0.006	1.000	
SPEC ENTH, BTU/LB MOLE			10,639	-89,910	-12,339	-37,980	-154,146	11,306	10,918		
ENTHALPY, BTU/HR			5,292,692	-20,397,826	-1,776,738	-2,400,665	-12,775,736	0	64,637	-31,993,635	
MASS FLOW LB/HR			1,003	4,087	2,310	1,770	3,648	0	166	12,984	
ENTHALPY IN, BTU/HR				-4.4362E+07							
ENTHALPY OUT, BTU/HR				-3.1994E+07							
RU HEAT LOSS, BTU/HR				0	INCLUDED IN STACK LOSS						
NET ENTHALPY, IN - OUT, BTU/HR				-12,368,442	TO BE SUBTRACTED FROM STACK WASTE HEAT IN STACK BALANCE						

CELL STACK

										FUEL UTILIZATION=H2 CONSUMED/H2 CONSUMED +H2 EXIT +CO EXIT =	
CELL STACK POWER, KW	17619.00	60,133.647 BTU/HR									0.780
CELL VOLTAGE, V/C	0.817										
FUEL CELL EFFICIENCY, %	0.637										
CURRENT DENSITY, A/M ²	0.12	H ₂	CO ₂ TRNSFE	H ₂ O FORMED	O ₂						
CONSUMPTIONS, LB MOLES/HR		886.773	886.773	886.773	443.386						
STATION ANODE IN	TEMP, F 11	579.4 DEG C									
GAS	H ₂	H ₂ O	CH ₄	CO	CO ₂	O ₂	N ₂	TOTAL			
MOLECULAR WEIGHT	2.016	18.016	16.042	28.010	44.010	32.000	28.016	12.725			
MOLE FLOW, LB MOLES/HR	497.47	226.87	143.99	63.21	82.88	0.00	5.92	1020.34			
MOLE FRACTION	0.488	0.222	0.141	0.062	0.081	0.000	0.006	1.000			
SPEC ENTH, BTU/LB MOLE	10,639	-89,910	-12,339	-37,980	-154,146	11,306	10,918				
ENTHALPY, BTU/HR	5,292,682	-20,387,826	-1,776,738	-2,400,665	-12,775,736	0	64,637	-31,993,635			
MASS FLOW, LB/HR	1,003	4,087	2,310	1,770	3,648	0	166	12,984			
Cp, BTU/LB MOLE/DEG F	7.16	9.42	15.67	7.71	12.49	8.14	7.59	0.09			
NON EQUILIB OUT FLOWS OF H ₂ , CO, H ₂ O, & CO ₂ (ASSUMING 100% CH ₄ CONVERSION)											
MOLE FLOW, LB MOLES/HR	42,668	969,652		207,198	969,653			2189,171			
MOLE FRACTION	0.019	0.443		0.095	0.443			1.000			
EQUILIB OUT FLOWS		B	A	D							
MOLE FRACTION	0.072	0.391	0.042		0.495			1.000			
MOLE FLOW, LB MOLES/HR	158,955	855,365	92,911		1083,940			2189,171			
EQUILIB TEMP	=	1170.00									
SHIFT EQUILIBRIUM CONSTANT =		2.141									
				a=	1.14073			0.052205605			
				b=	-1.61323						
				c=	0.08111						
SHIFT EQUILIBRIUM CALCULATION FOR ANODE EXIT STREAM											
TEMP, DEG F =	1170.00										
TEMP, DEG R =	1630										
V=1/T=	0.0006135										
log10Kp=	0.33056148										
Kp =	2.1407										
STATION ANODE OUT FLOW	TEMP, F 12	632.2 DEG C									
GAS	H ₂	H ₂ O	CH ₄	CO	CO ₂	O ₂	N ₂	TOTAL			
MOLECULAR WEIGHT	2.016	18.016	16.042	28.010	44.010	32.000	28.016	30.158			
MOLE FLOW, LB MOLES/HR	156.95	855.37	0.00	92.91	1083.94	0.00	5.92	2195.09			
MOLE FRACTION	0.072	0.390	0.000	0.042	0.494	0.000	0.003	1.000			
SPEC ENTH, BTU/LB MOLE	11,316	-89,008	-10,821	-37,243	-152,949	12,083	11,644				
ENTHALPY, BTU/HR	1,776,111	-76,134,278	0	-3,460,291	-165,787,892	0	68,934	-243,537,416			
MASS FLOW, LB/HR	316	15,410	0	2,602	47,704	0	166	66,199			
Cp, BTU/LB MOLE/DEG F	7.13	9.58	16.23	7.79	12.68	8.21	7.67	0.11			

CELL STACK

CATHODE					CATHODE OXYGEN UTILIZATION= O2 CONSUMED/O2 IN=						0.50
STATION	17	TEMP, F	1045.5	563.1	DEG C						
CATHODE IN FLOW FROM E-9											
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT			2.016	18.016	16.042	28.010	44.010	32.000	28.016	29.740	
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	1191.46	883.15	3804.52	6940.15	
MOLE FRACTION			0.000	0.153	0.000	0.000	0.172	0.127	0.548	1.000	
SPEC ENTH, BTU/LB MOLE			10,430	-90,188	-12,800	-38,207	-154,514	11,066	10,695		
ENTHALPY, BTU/HR		0	-95,690,854		0	0	-184,097,655	9,772,926	40,688,409	-229,327,173	
MASS FLOW LB/HR		0	19,115		0	0	52,436	28,261	106,587	206,400	
Cp, BTU/LB MOLE/DEG F		7.18	9.37		15.50	7.68	12.43	8.12	7.57	0.09	
STATION	18	TEMP, F	1179.4	637.4	DEG C						
CATHODE OUT FLOW											
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT			2.016	18.016	16.042	28.010	44.010	32.000	28.016	27.306	
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99	
MOLE FRACTION			0.000	0.189	0.000	0.000	0.054	0.078	0.678	1.000	
SPEC ENTH, BTU/LB MOLE			11,383	-88,918	-10,668	-37,170	-152,830	12,161	11,716		
ENTHALPY, BTU/HR		0	-94,343,541		0	0	-46,565,293	5,347,817	44,575,382	-90,985,635	
MASS FLOW LB/HR		0	19,115		0	0	13,409	14,073	106,587	153,185	
Cp, BTU/LB MOLE/DEG F		7.13	9.59		16.29	7.80	12.69	8.22	7.68	0.08	
STACK HEAT BALANCE									ANODE	CATHODE	
POWER OUTPUT, BTU/HR			=	60,133,647			STREAM DELTA T =			95.00	133.90
HEAT LOSS FROM STACKS , BTU/HR			=	700,000							
HEAT ABSORBED BY RU			=	-12,368,442			LOGIC FOR CATHODE EXIT TEMP TO BALANCE STACK ENERGY				
ANODE STREAM ENTHALPY IN, BTU/HR			=	-31,993,635			CATHODE EXIT TEMP CORRECTION TO NULL ENTHALPY DELTA				
ANODE STREAM ENTHALPY OUT, BTU/HR			=	-243,537,416			LOGIC FOR ITERATION		FALSE	FALSE	
CATH STRM ENTHALPY IN , BTU/HR			=	-229,327,173			ITERATION INCREMENT		24.31	-24.91	
CATH STRM ENTHALPY OUT, BTU/HR			=	-90,985,635			TEMP CHANGE =		-0.6		
NET ENTHALPY , BTU/HR IN-OUT			=	153							
</											

APPENDIX 5
COMPRESSOR SHEET

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FIRST INTERCOOLER E-10										
STATION	49	TEMP, F	88.5	30.3	DEG C					
COLD SIDE INLET										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	18.016
MOLE FLOW, LB MOLES/HR			0.00	2000.00	0.00	0.00	0.00	0.00	0.00	2000.00
MOLE FRACTION			0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.000
SPEC ENTH, BTU/LB MOLE			3,709	-117,106	-24,378	-45,168	-165,048	3,791	3,796	
ENTHALPY, BTU/HR			0	-234,211,008	0	0	0	0	0	-234,211,008
MASS FLOW LB/HR			0	36,032	0	0	0	0	0	36,032
STATION	50	TEMP, F	198.6	92.5	DEG C					
COLD SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	18.016
MOLE FLOW, LB MOLES/HR			0.00	2000.00	0.00	0.00	0.00	0.00	0.00	2000.00
MOLE FRACTION			0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.000
SPEC ENTH, BTU/LB MOLE			4,487	-115,086	-23,384	-44,387	-164,010	4,582	4,577	
ENTHALPY, BTU/HR			0	-230,171,700	0	0	0	0	0	-230,171,700
MASS FLOW LB/HR			0	36,032	0	0	0	0	0	36,032
STATION		STATION		STATION	ASSUMED EFFECTIVENESS, e =		0.762			
Thi, F	=	29	242	30	CALCULATED Tho F =		123.4	=Thi-eCmin/Ch(Thi-Tci)		
Tci, F	=	49	86	50	COLD SIDE EXIT		198.6			
Ch=DH/DT	=	BTU/HR F	34176		ENERGY BALANCE	IN	OUT	DELTA		
Cc=DH/DT	=	BTU/HR F	36032		HOT SIDE		16,331,549	12,292,241	4,039,308	
Cmin	=	BTU/HR F	34176		COLD SIDE		-234,211,008	-230,171,700	-4,039,308	
Thi-Tci, F	=		155		TOTAL		-217,879,459	-217,879,459	0	
Cmin/Cmax	=		1.05							
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/Cmin(Thi-Tci)		0.762			
CALCULATED EFFECTIVENESS FOR SELECTED Tho					e = Ch(Thi-Tho)/Cmin(Thi-Tci)		0.762			
2ND STAGE COMPRESSOR										
STATION	30	TEMP, F	123.4	50.8	DEG C					
2ND STAGE COMPRESSOR INLET AIR							PRESSURE IN, PSIA =			35.062
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.00	48.70	0.00	0.00	14.61	1008.09	3798.60	4870.00
MOLE FRACTION			0.00000	0.01000	0.00000	0.00000	0.00300	0.20700	0.78000	1.000
SPEC ENTH, BTU/LB MOLE			3,965	-98,162	-24,061	-44,911	-184,714	4,050	4,053	
ENTHALPY, BTU/HR			0	-4,780,512	0	0	-2,406,234	4,082,915	15,396,073	12,292,241
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201

GTCOMPRESSOR

COMPRESSOR EXIT TEMP				SECOND STAGE COMPRESSOR WORK, Wci (ADIABATIC)						
To = Ti (Po/Pi)^(K-1/K) + (Wca-Wci-HL)wcCp -460				R =1544/778.3= 1.984 BTU /lb mole deg R						
COMP-2				Wci =BTU/HR, kW						
123.4				wc = LB/HR						
50.8 DEG C				m = molecular wt lbs/lb mole						
165.3 DEG C				Po/Pi = pressure ratio psi						
2.470				k = constant for gas, Cp/Cv						
86.60				Cp , BTU/LB F						
				k-1/k						
				n = ADIABATIC efficiency						
				Wca= BTU/HR, kW						
				ACTUAL WORK						
				7,004.592						
				2,052						

GTCOMPRESSOR

		STATION		STATION	ASSUMED EFFECTIVENESS, e =	0.847				
Thi, F	=	31	328	32	CALCULATED Tho F =	123.4	=Thi-eCmin/Ch(Thi-Tci)			
Tci, F	=	51	86	52	COLD SIDE EXIT	208.0				
Ch=DH/DT	=	BTU/HR F	34279		ENERGY BALANCE	IN	OUT	DELTA		
Cc=DH/DT	=	BTU/HR F	57651		HOT SIDE	19,297,046	12,292,164	7,004,882		
Cmin	=	BTU/HR F	34279		COLD SIDE	-374,737,613	-367,732,730	-7,004,882		
Thi-Tci, F	=		241		TOTAL	-355,440,566	-355,440,566	0		
Cmin/Cmax	=		1.68							
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/ Cmin(Thi-Tci)	0.847				
CALCULATED EFFECTIVENESS FOR SELECTED Tho					e = Ch(Thi-Tho)/ Cmin(Thi-Tci)	0.847				
3RD STAGE COMPRESSOR						AIR FLOW, LB MOLES /HR =		4483		
						WATER VAPOR PRESSURE,PSIA		0.147		
STATION	32	TEMP, F	123.4	50.8	DEG C	DRY FRACTION		0.99000		
3RD STAGE COMPRESSOR AIR INLET						PRESSURE IN , PSIA =		85.60		
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.00	48.70	0.00	0.00	14.61	1008.09	3798.60	4870.00
MOLE FRACTION			0.00000	0.01000	0.00000	0.00000	0.00300	0.20700	0.78000	1.000
SPEC ENTH, BTU/LB MOLE			3,965	-98,162	-24,061	-44,911	-164,714	4,050	4,053	
ENTHALPY, BTU/HR			0	-4,780,513	0	0	-2,406,235	4,082,899	15,396,013	12,292,164
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
COMPRESSOR EXIT TEMP						THIRD STAGE COMPRESSR WORK, Wci, (ADIABATIC)				
To = Ti (Po/Pi)^(K-1/K) +(Wca-Wci-HL)/wcCp -460						=(wc/m) RTci (k/k-1)/((Po/Pi)^(k-1/k)-1)				
						R =1544/778.3= 1.984 BTU /lb mole deg R				
					COMP-3	Wci =BTU/HR, kW	IDEAL WORK	5,820,637	1,705	
TEMP IN , F	Tci		123.4	50.8	DEG C	wc = LB/HR		140,201		
TEMP OUT, F	Tco		331.4	166.3	DEG C	m = molecular wt lbs/lb mole		28.789		
PRESSURE RATIO	Po/Pi		2.470			Po/Pi = pressure ratio psi		2.470		
PRESSURE OUT ,PSIA =						k = constant for gas, Cp/Cv		1.4035		
						Cp , BTU/LB F		0.2445		
						k-1/k		0.287		
						n = ADIABATIC efficiency		0.83		
						Wca= BTU/HR, kW	ACTUAL WORK	7,012,816	2,055	
STATION	33	TEMP, F	328.0	164.4	DEG C					
3RD STAGE COMPRESSOR AIR EXIT										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.00	48.70	0.00	0.00	14.61	1008.09	3798.60	4870.00
MOLE FRACTION			0.00000	0.01000	0.00000	0.00000	0.00300	0.20700	0.78000	1.000
SPEC ENTH, BTU/LB MOLE			5,388	-96,494	-22,118	-43,479	-162,732	5,516	5,481	
ENTHALPY, BTU/HR			0	-4,699,261	0	0	-2,377,277	5,560,346	20,821,300	19,305,108
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201

ENTHALPY IN , BTU/HR		1.2292E+07				HEAT BALANCE		FALSE		FALSE	
COMPRESSOR POWER IN BT/HR		7.0128E+06				LOGIC FOR ITERATION		6.09		-9.48	
ENTHALPY OUT, BTU/HR		1.9305E+07				ITERATION INCREMENT					
HEAT LOSS, BTU/HR		0				TEMP CHANGE =		-3.39			
NET ENERGY, IN - OUT , BTU/HR		-128									
INTERCOOLER COOLANT LOOP AND NATURAL DRAFT TOWER											
STATION		53		TEMP, F		204.4		95.8		DEG C	
COOLANT MIX FROM INTERCOOLERS											
GAS						H2		H2O		CH4	
MOLECULAR WEIGHT						2.016		18.016		16.042	
MOLE FLOW, LB MOLES/HR						0.00		5200.00		0.00	
MOLE FRACTION						0.00000		1.00000		0.00000	
SPEC ENTH, BTU/LB MOLE						4.524		-114.982		-23.532	
ENTHALPY, BTU/HR						0		-597,904,821		0	
MASS FLOW LB/HR						0		93,683		0	
ENTHALPY IN, BTU/HR											
ENTHALPY OUT, BTU/HR		50+52						-5.9790E+08			
HEAT LOSS, BTU/HR								-5.9790E+08		0	
NET ENTHALPY, IN - OUT , BTU/HR								390			
TEMP CHANGE =											
STATION		47		TEMP, F		86.5		30.3		DEG C	
COOLANT FROM COOLING TOWER											
GAS						H2		H2O		CH4	
MOLECULAR WEIGHT						2.016		18.016		16.042	
MOLE FLOW, LB MOLES/HR						0.00		5200.00		0.00	
MOLE FRACTION						0.00000		1.00000		0.00000	
SPEC ENTH, BTU/LB MOLE						3.701		-117,106		-24,862	
ENTHALPY, BTU/HR						0		-608,948,620		0	
MASS FLOW LB/HR						0		93,683		0	
COOLING TOWER AIR											
NATURAL DRAFT TOWER AIR FLOW, LB MOLES /HR =											
WATER VAPOR PRESSURE, PSIA											
DRY FRACTION											
STATION		54		TEMP, F		59.0		15.0		DEG C	
COOLING TOWER INLET AIR											
GAS						H2		H2O		CH4	
MOLECULAR WEIGHT						2.016		18.016		16.042	
MOLE FLOW, LB MOLES/HR						0.00		150.00		0.00	
MOLE FRACTION						0.00000		0.01000		0.00000	
SPEC ENTH, BTU/LB MOLE						3.519		-98,679		-24,607	
ENTHALPY, BTU/HR						0		-14,801,866		0	
MASS FLOW LB/HR						0		2,702		0	

GTCOMPRESSOR

STATION	55	TEMP, F	164.3	73.5	DEG C		DRY FRACTION			1.00000
COOLING TOWER EXIT AIR										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.00	150.00	0.00	0.00	45.00	3104.99	11700.00	14999.99
MOLE FRACTION			0.00000	0.01000	0.00000	0.00000	0.00300	0.20700	0.78000	1.000
SPEC ENTH, BTU/LB MOLE			4,248	-97,832	-23,698	-44,626	-164,335	4,339	4,338	
ENTHALPY, BTU/HR			0	-14,674,863	0	0	-7,394,343	13,471,794	50,753,406	42,155,995
MASS FLOW LB/HR			0	2,702	0	0	1,980	99,360	327,787	431,830
		STATION		STATION	ASSUMED EFFECTIVENESS, e =			0.811		
Thi, F	=	53	204	47	SELECTED Tho			86.5	=Thi-eCmin/Ch(Thi-Tci)	
Tci, F	=	54	59	55	COLD SIDE EXIT			164.3		
Ch=DH/DT	=	BTU/HR F	93683		ENERGY BALANCE			IN	OUT	DELTA
Cc=DH/DT	=	BTU/HR F	104902		HOT SIDE			-597,904,821	-608,948,620	11,043,800
Cmin	=	BTU/HR F	93683		COLD SIDE			31,112,195	42,155,995	-11,043,800
Thi-Tci, F	=		145		TOTAL			-566,792,625	-566,792,625	0
Cmin/Cmax	=		0.89							
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/ Cmin(Thi-Tci)			0.811		
CALCULATED EFFECTIVENESS FOR SELECTED Tho					e = Ch(Thi-Tho)/ Cmin(Thi-Tci)			0.811		
COOLING LOOP COOLANT PUMP										
	FLOW, LBMOLES/HR =		5200							
	FLOW LBS/HR		93683							
	FLOW, GPM		187							
	HEAD, PSI =		10							
	EFFICIENCY		0.7							
PUMP POWER, KW =		FLOW(GPM)XHEAD(PSI)/ 2300 =			1.16					
		EFFICIENCY								
PARASITIC POWER FO RCONTROLS AND MISC , KW =					10					
TOTAL PARASITIC POWER, KW					11.16					

APPENDIX 6

AIR PREHEATER SHEET

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AIR PREHEATERS

3/3/99 14:19		AIR PREHEATER E-4 AND E-1									
HEAT EXCHANGER E-4											
STATION	22	TEMP, F	845	451.8	DEG C						
HOT SIDE INLET											
GAS		H2		H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT		2.016		18.016	16.042	28.01	44.01	32	28.016	27.306	
MOLE FLOW, LB MOLES/HR		0		1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99	
MOLE FRACTION		0.000		0.189	0	0.000	0.054	0.078	0.678	1.000	
SPEC ENTH, BTU/LB MOLE		9,013		-92,030	-15,773	-39,726	-156,960	9,459	9,197		
ENTHALPY, BTU/HR		0		-97,645,380	0	0	-47,623,817	4,159,697	34,988,772	-106,320,727	
MASS FLOW LB/HR		0		19,115	0	0	13,409	14,073	106,587	153,185	
STATION	23	TEMP, F	447.9	231.0	DEG C						
HOT SIDE EXIT											
GAS		H2		H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT		2.016		18.016	16.042	28.01	44.01	32	28.016	27.306	
MOLE FLOW, LB MOLES/HR		0.00		1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99	
MOLE FRACTION		0.000		0.189	0	0.000	0.054	0.078	0.678	1.000	
SPEC ENTH, BTU/LB MOLE		6,225		-95,493	-20,828	-42,629	-161,480	6,400	6,326		
ENTHALPY, BTU/HR		0		-101,320,472	0	0	-49,200,844	2,814,602	24,066,890	-123,639,825	
MASS FLOW LB/HR		0		19,115	0	0	13,409	14,073	106,587	153,185	
STATION	33	TEMP, F	328.0	164.4	DEG C						
COLD SIDE INLET FROM GT 3RD STAGE COMPRESSOR											
GAS		H2		H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT		2.016		18.016	16.042	28.01	44.01	32	28.016	28.789	
MOLE FLOW, LB MOLES/HR		0.000		48.700	0.000	0.000	14.609	1008.086	3798.601	4869.995179	
MOLE FRACTION		0.000		0.010	0.000	0.000	0.003	0.207	0.780	1.000	
SPEC ENTH, BTU/LB MOLE		5,388		-96,494	-22,118	-43,479	-162,732	5,516	5,481		
ENTHALPY, BTU/HR		0		-4,699,261	0	0	-2,377,277	5,560,346	20,821,300	19,305,108	
MASS FLOW LB/HR		0		877	0	0	643	32,259	106,422	140,201	
STATION	34	TEMP, F	816.0	435.6	DEG C						
COLD SIDE EXIT											
GAS		H2		H2O	CH4	CO	CO2	O2	N2	TOTAL	
MOLECULAR WEIGHT		2.016		18.016	16.042	28.01	44.01	32	28.016	28.789	
MOLE FLOW, LB MOLES/HR		0.00		48.70	0.00	0.00	14.61	1008.09	3798.60	4870.00	
MOLE FRACTION		0.000		0.010	0.000	0.000	0.003	0.207	0.780	1.000	
SPEC ENTH, BTU/LB MOLE		8,807		-92,293	-16,185	-39,945	-157,309	9,228	8,981		
ENTHALPY, BTU/HR		0		-4,494,674	0	0	-2,298,060	9,302,178	34,114,763	36,624,206	
MASS FLOW LB/HR		0		877	0	0	643	32,259	106,422	140,201	
Thi, F	=	22	845	23	ASSUMED EFFECTIVENESS, e =			0.943			
Tci, F	=	33	328	34	CALCULATED Tho F =			447.9	=Thi-eCmin/Ch(Thi-Tci)		
Ch=DH/DT	=	BTU/HR F	43586		CALCULATED Tco F			816.0	=Tci+eCmin/Cc(Thi-Tci)		
Cc=DH/DT	=	BTU/HR F	35488		ENERGY BALANCE			IN	OUT	DELTA	
Cmin	=	BTU/HR F	35488		HOT SIDE			-106,320,727	-123,639,825	17,319,099	
Thi-Tci, F	=		517		COLD SIDE			19,305,108	36,624,206	-17,319,099	
Cmin/Cmax	=		0.81		TOTAL			-87,015,619	-87,015,619	0	
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/ Cmin(Thi-Tci)			0.943			

AIR PREHEATERS

HEAT EXCHANGER E-1										
STATION	19	TEMP, F	1,179	637.4	DEG C					
HOT SIDE INLET										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	27.306
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678	1.000
SPEC ENTH, BTU/LB MOLE			11,383	-88,918	-10,668	-37,170	-152,830	12,161	11,716	
ENTHALPY, BTU/HR			0	-94,343,541	0	0	-46,565,293	5,347,817	44,575,382	-90,985,635
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587	153,185
STATION	20	TEMP, F	985.7	529.8	DEG C					
HOT SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	27.306
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	304.69	439.77	3804.52	5609.99
MOLE FRACTION			0.000	0.189	0	0.000	0.054	0.078	0.678	1.000
SPEC ENTH, BTU/LB MOLE			10,005	-90,745	-13,716	-38,665	-155,255	10,582	10,243	
ENTHALPY, BTU/HR			0	-96,282,521	0	0	-47,304,245	4,653,457	38,970,636	-99,962,673
MASS FLOW LB/HR			0	19,115	0	0	13,409	14,073	106,587	153,185
STATION	34	TEMP, F	816.0	435.6	DEG C					
COLD SIDE INLET										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.00	48.70	0.00	0.00	14.61	1008.09	3798.60	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			8,807	-92,293	-16,185	-39,945	-157,309	9,228	8,981	
ENTHALPY, BTU/HR			0	-4,494,674	0	0	-2,298,060	9,302,178	34,114,763	36,624,206
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
STATION	35	TEMP, F	1058.0	570.0	DEG C					
COLD SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.00	48.70	0.00	0.00	14.61	1008.09	3798.60	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			10,518	-90,070	-12,605	-38,111	-154,359	11,168	10,789	
ENTHALPY, BTU/HR			0	-4,386,427	0	0	-2,254,955	11,257,797	40,984,829	45,601,244
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
STATION		STATION		STATION	ASSUMED EFFECTIVENESS, e =					
Thi, F	=	19	1,179	20	CALCULATED Tho F =		985.7	=Thi-eCmin/Ch(Thi-Tci)		
Tci, F	=	34	816	35	CALCULATED Tco F		1058.0	=Tci+eCmin/Cc(Thi-Tci)		
Ch=DH/DT	=	BTU/HR F	46334		ENERGY BALANCE	IN	OUT	DELTA		
Cc=DH/DT	=	BTU/HR F	37095		HOT SIDE	-90,985,635	-99,962,673	8,977,038		
Cmin	=	BTU/HR F	37095		COLD SIDE	36,624,206	45,601,244	-8,977,038		
Thi-Tci, F	=		363		TOTAL	-54,361,429	-54,361,429	0		
Cmin/Cmax	=		0.80							
CALCULATED EFFECTIVENESS FOR SELECTED Tco				e = Cc(Tco-Tci)/Cmin(Thi-Tci)				0.666		

APPENDIX 7

TURBINE SHEET

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GTTURBINE

3/3/99 14:19		TURBINE EXPANDER/GENERATOR									
P1, = FIRST TURBINE INLET PRESSURE, PSIA		207.44						TURBINE EFFICIENCIES =		0.83	
P2 = 1ST STAGE OUTLET PRESSURE		22									
P3 = 2ND STAGE INLET PRESSURE		21									
P4= 2ND STAGE OUTLET PRESSURE, PSIA		15.5						PRESSURE RATIO 1ST TURBINE =		0.1061	
								PRESSURE RATION SECOND TURBINE =		0.7381	
STATION		36		TEMP, F		1526.0		830.0		DEG C	
FIRST STAGE TURBINE INLET											
		GAS		H2		H2O		CH4		CO	
								CO2		O2	
										N2	
										TOTAL	
MOLECULAR WEIGHT		2.016		18.016		16.042		28.01		44.01	
MOLE FLOW, LB MOLES/HR		0.000		48,700		0.000		0.000		14.609	
MOLE FRACTION		0.000		0.010		0.000		0.000		0.003	
SPEC ENTH, BTU/LB MOLE		13,887		-85,489		-4,685		-34,418		-148,322	
ENTHALPY, BTU/HR		0		-4,163,290		0		0		-2,166,767	
MASS FLOW LB/HR		0		877		0		0		643	
										32,259	
										106,422	
										140,201	

GT TURBINE

STATION	38	TEMP, F	1220.0	660.0	DEG C					
SECOND STAGE TURBINE INLET										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.000	48.700	0.000	0.000	14.609	1008.086	3798.601	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			11,674	-88,527	-10,001	-36,852	-152,312	12,495	12,029	
ENTHALPY, BTU/HR			0	-4,311,249	0	0	-2,225,060	12,596,319	45,694,424	51,754,434
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
SECOND STAGE TURBINE WORK, Wt, (ADIABATIC)										
= (wt/m) R Tti (K/K-1) (1-(Po/Pi)^(k-1/k))										
R = 1.9838 BTU /lb mole R										
To = Ti (Po/Pi)^(K-1/K) + (WtL-Wta-HL)/wtCp -460										
Wtideal = BTU/HR, kW										
wt = LB/HR										
m = molecular wt lbs/lb mole										
Po/Pi = pressure ratio										
k = constant for gas, Cp/Cv										
Cp, BTU/LB F										
k-1/k										
n = ADIABATIC efficiency										
Wtactual = BTU/HR, kW										
STATION	39	TEMP, F	1116.4	602.4	DEG C					
SECOND STAGE TURBINE EXIT										
	GAS		H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.000	48.700	0.000	0.000	14.609	1008.086	3798.601	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			10,934	-89,519	-11,685	-37,660	-153,627	11,844	11,234	
ENTHALPY, BTU/HR			0	-4,359,584	0	0	-2,244,267	11,737,784	42,672,260	47,806,193
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
ENTHALPY IN, BTU/HR				5.1754E+07						
ENTHALPY OUT, BTU/HR				5.1744E+07						
HEAT LOSS, BTU/HR				10000						
NET ENTHALPY, IN - OUT, BTU/HR				90						
HEAT BALANCE										
LOGIC FOR ITERATION										
ITERATION INCREMENT										
TEMP CHANGE =										
TURBINE GENERATOR WORK SUMMARY										
WORK, KW										
FIRST STAGE COMPRESSOR										
SECOND STAGE COMPRESSOR										
THIRD STAGE COMPRESSOR										
FIRST STAGE TURBINE										
SECOND STAGE TURBINE										
NET POWER										
GENERATOR EFFICIENCY										
NET AC POWER										

APPENDIX 8

BURNER SHEET

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36224	BURNER CATALYTIC BURNER, E-8 PLUS E-9										
STATION	13	TEMP, F	1,170.00	632.2 DEG C							
STACK ANODE OUT FLOW TO BURNER											
GAS											
MOLECULAR WEIGHT	2.016	H2	18.016	CH4	16.042	CO	28.010	CO2	44.010	N2	TOTAL
MOLE FLOW, LB MOLES/HR	156.955		855.365		0.000		92.911		1083.940	5.920	30.158
MOLE FRACTION	0.072		0.390		0.000		0.042		0.000	0.003	1.000
SPEC ENTH, BTU/LB MOLE	11,316		-89,008		-10,821		-37,243		-152,949	11,644	
ENTHALPY, BTU/HR	1,776,111		-76,134,278		0		-3,460,291		-165,787,892	68,934	-243,537,416
MASS FLOW LB/HR	316		15,410		0		2,602		47,704	166	66,199
STATION	39	TEMP, F	1,116.39	602.4 DEG C							
2ND STAGE TURBINE EXIT											
GAS											
MOLECULAR WEIGHT	2.016	H2	18.016	CH4	16.042	CO	28.010	CO2	44.010	N2	TOTAL
MOLE FLOW, LB MOLES/HR	0.000		48,700		0.000		0.000		14,609	37,98.601	28.789
MOLE FRACTION	0.000		0.010		0.000		0.000		0.003	0.780	1.000
SPEC ENTH, BTU/LB MOLE	10,934		-89,519		-11,685		-37,660		-153,627	11,234	
ENTHALPY, BTU/HR	0		-4,359,582		0		0		-2,244,266	42,672,376	47,806,344
MASS FLOW LB/HR	0		877		0		0		643	106,422	140,201
STATION	14	TEMP, F	1,137.1	613.9 DEG C							
MIXED ANODE EXHAUST AND TURBINE EXHAUST (BEFORE BURNING											
GAS											
MOLECULAR WEIGHT	2.016	H2	18.016	CH4	16.042	CO	28.010	CO2	44.010	N2	TOTAL
MOLE FLOW, LB MOLES/HR	156.955		904.065		0.000		92.911		1098.549	3804.521	7065.09
MOLE FRACTION	0.022		0.128		0.000		0.013		0.155	0.143	1.000
SPEC ENTH, BTU/LB MOLE	11,081		-89,323		-11,354		-37,499		-153,367	11,813	11,392
ENTHALPY, BTU/HR	1,739,203		-80,753,567		0		-3,484,110		-168,480,597	43,339,546	-195,731,211
MASS FLOW LB/HR	316		16,288		0		2,602		48,347	106,587	206,400
ENTHALPY IN, BTU/HR											
ENTHALPY OUT, BTU/HR											
HEAT LOSS, BTU/HR											
NET ENTHALPY, IN - OUT , BTU/HR											
HEAT BALANCE											
LOGIC FOR ITERATION											
ITERATION INCREMENT											
TEMP CHANGE =											
STATION	15	TEMP, F	1,580.3	860.2 DEG C							
CATALYTIC BURNER EXHAUST											
GAS											
MOLECULAR WEIGHT	2.016	H2	18.016	CH4	16.042	CO	28.010	CO2	44.010	N2	TOTAL
MOLE FLOW, LB MOLES/HR	0.000		1061.020		0.000		0.000		1191.460	3804.521	6940.15
MOLE FRACTION	0.000		0.153		0.000		0.000		0.172	0.127	1.000
SPEC ENTH, BTU/LB MOLE	14,284		-84,933		-3,694		-33,979		-147,600	15,512	14,862
ENTHALPY, BTU/HR	0		-90,115,921		0		0		-17,585,9050	56,544,557	-195,731,287
MASS FLOW LB/HR	0		19,115		0		0		52,436	106,587	206,400
ENTHALPY IN, BTU/HR											
ENTHALPY OUT, BTU/HR											
HEAT LOSS, BTU/HR											
NET ENTHALPY, IN - OUT , BTU/HR											
HEAT BALANCE											
LOGIC FOR ITERATION											
ITERATION INCREMENT											
TEMP CHANGE =											

HEAT EXCHANGER E-8										
STATION	15	TEMP, F	1,580	860.2	DEG C					
HOT SIDE INLET(CAT BURNER EXIT)										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	29.740
MOLE FLOW, LB MOLES/HR			0.000	1061.020	0.000	0.000	1191.460	883.153	3804.521	6940.153472
MOLE FRACTION			0.000	0.153	0	0.000	0.172	0.127	0.548	1.000
SPEC ENTH, BTU/LB MOLE			14,284	-84,933	-3,694	-33,979	-147,600	15,512	14,862	
ENTHALPY, BTU/HR			0	-90,115,921	0	0	-175859050	13,699,127	56,544,557	-195731287
MASS FLOW LB/HR			0	19,115	0	0	52,436	28,261	106,587	206,400
STATION	16	TEMP, F	1,297.1	702.8	DEG C					
HOT SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	29.740
MOLE FLOW, LB MOLES/HR			0.00	1061.02	0.00	0.00	1191.46	883.15	3804.52	6940.15
MOLE FRACTION			0.000	0.153	0	0.000	0.172	0.127	0.548	1.000
SPEC ENTH, BTU/LB MOLE			12,227	-87,776	-8,708	-36,246	-151,321	13,134	12,627	
ENTHALPY, BTU/HR			0	-93,132,452	0	0	-180293353	11,599,304	48,039,819	-213786682
MASS FLOW LB/HR			0	19,115	0	0	52,436	28,261	106,587	206,400
STATION	35	TEMP, F	1058.0	570.0	DEG C					
COLD SIDE INLET FROM E-1 EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.000	48.700	0.000	0.000	14.609	1008.086	3798.601	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			10,518	-90,070	-12,605	-38,111	-154,359	11,168	10,789	
ENTHALPY, BTU/HR			0	-4,386,427	0	0	-2,254,955	11,257,797	40,984,829	45,601,244
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
STATION	36	TEMP, F	1526.0	830.0	DEG C					
COLD SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.000	48.700	0.000	0.000	14.609	1008.086	3798.601	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			13,887	-85,489	-4,685	-34,418	-148,322	15,053	14,430	
ENTHALPY, BTU/HR			0	-4,163,290	0	0	-2,166,767	15,174,326	54,812,371	63,656,640
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
	STATION		STATION	ASSUMED EFFECTIVENESS, e =			0.896			
Thi, F	=	15	1,580	16	CALCULATED Tho F =		1297.1		=Thi-eCmin/Ch(Thi-Tci)	
Tci, F	=	37	1,058	38	CALCULATED Tco F		1526.0		=Tci+eCmin/Cc(Thi-Tci)	
Ch=DH/DT	=	BTU/HR F	63757		ENERGY BALANCE		IN	OUT	DELTA	
Cc=DH/DT	=	BTU/HR F	38580		HOT SIDE			-195731287	-213786682	18,055,396
Cmin	=	BTU/HR F	38580		COLD SIDE			45601244	63656640	-18,055,396
Thi-Tci, F	=		522		TOTAL			-150130043	-150130043	0
Cmin/Cmax	=		0.61							
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/ Cmin(Thi-Tci)			0.896		

BURNER

HEAT EXCHANGER E-9										
STATION	16	TEMP, F	1,297	702.8	DEG C					
HOT SIDE INLET										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	29.740
MOLE FLOW, LB MOLES/HR			0.000	1061.020	0.000	0.000	1191.460	883.153	3804.521	6940.153472
MOLE FRACTION			0.000	0.153	0	0.000	0.172	0.127	0.548	1.000
SPEC ENTH, BTU/LB MOLE			12,227	-87,776	-8,708	-36,246	-151,321	13,134	12,627	
ENTHALPY, BTU/HR			0	-93,132,452	0	0	-180,293,353	11,599,304	48,039,819	-213,786,682
MASS FLOW LB/HR			0	19,115	0	0	52,436	28,261	106,587	206,400
STATION	17	TEMP, F	1,045.5	563.1	DEG C					
HOT SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	29.740
MOLE FLOW, LB MOLES/HR			0.000	1061.020	0.000	0.000	1191.460	883.153	3804.521	6940.153472
MOLE FRACTION			0.000	0.153	0	0.000	0.172	0.127	0.548	1.000
SPEC ENTH, BTU/LB MOLE			10,430	-90,188	-12,800	-38,207	-154,514	11,066	10,695	
ENTHALPY, BTU/HR			0	-95,690,890	0	0	-184097708	9,772,900	40,688,305	-229327392
MASS FLOW LB/HR			0	19,115	0	0	52,436	28,261	106,587	206,400
STATION	37	TEMP, F	804.8	429.3	DEG C					
COLD SIDE INLET FROM 1ST STAGE TURBINE										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.000	48.700	0.000	0.000	14.609	1008.086	3798.601	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			8,728	-92,394	-16,341	-40,029	-157,443	9,139	8,898	
ENTHALPY, BTU/HR			0	-4,499,586	0	0	-2,300,010	9,212,797	33,800,524	36,213,725
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
STATION	38	TEMP, F	1220.0	660.0	DEG C					
COLD SIDE EXIT										
GAS			H2	H2O	CH4	CO	CO2	O2	N2	TOTAL
MOLECULAR WEIGHT			2.016	18.016	16.042	28.01	44.01	32	28.016	28.789
MOLE FLOW, LB MOLES/HR			0.000	48.700	0.000	0.000	14.609	1008.086	3798.601	4870.00
MOLE FRACTION			0.000	0.010	0.000	0.000	0.003	0.207	0.780	1.000
SPEC ENTH, BTU/LB MOLE			11,674	-88,527	-10,001	-36,852	-152,312	12,495	12,029	
ENTHALPY, BTU/HR			0	-4,311,249	0	0	-2,225,060	12,596,319	45,694,424	51,754,434
MASS FLOW LB/HR			0	877	0	0	643	32,259	106,422	140,201
Thi, F	=	STATION	16	STATION	ASSUMED EFFECTIVENESS, e =		0.843			
Tci, F	=	16	1,297	17	CALCULATED Tho F =		1045.5	=Thi-eCmin/Ch(Thi-Tci)		
Ch=DH/DT	=	39	805	40	CALCULATED Tco F =		1220.0	=Tci+eCmin/Cc(Thi-Tci)		
Cc=DH/DT	=	BTU/HR F	61771		ENERGY BALANCE	IN	OUT	DELTA		
Cmin	=	BTU/HR F	37426		HOT SIDE		-213786682	-229327392	15,540,710	
Thi-Tci, F	=	BTU/HR F	37426		COLD SIDE		36,213,725	51,754,434	-15,540,710	
Cmin/Cmax	=		492		TOTAL		-177572958	-177572958	0	
			0.61							
CALCULATED EFFECTIVENESS FOR SELECTED Tco					e = Cc(Tco-Tci)/ Cmin(Thi-Tci)		0.843			
CALCULATED EFFECTIVENESS FOR SELECTED Tho					e=Ch(Thi-Tho)/Cmin(Thi-Tci)		0.843			

APPENDIX 9

SUMMARY SHEET FOR EXAMPLE CASE

hefplant.xls

SUMMARY

3/4/99 10:39		HIGH EFFICIENCY POWER PLANT PROCESS SUMMARY									
EXCEL 97 WORK BOOK PREPARED BY R.A.Sanderson P.E.											
FEBRUARY 1999		FIXED		CASE	2						
INPUT PARAMETERS		REFERENCE	+/- DEVIATION	OUTPUT CHARACTERISTICS				REQUIREMENT			
CH4 INPUT, MOLES/HR	=	296.00	0	NET AC POWER, KW				=	20,820	20,000	
PROCESS AIR FLOW, MOLES/HR	=	4870	-335	NET AC LHV EFFICIENCY, %				=	72.50	> 70	
AMBIENT AIR TEMP F	=	59	0	PARASITIC LOSSES, KW				=	11		
WATER VAPOR PRESS, PSIA	=	0.147	0	GROSS AC POWER				=	20831		
FUEL LOWER HEATING VALUE, BTU/SCF	=	872.5	N/A	PLANT EXHAUST TEMP, F				=	200.1		
CELL STACK				FUEL CELLS							
CELL VOLTAGE	=	0.817	0	FUEL CELL AC OUTPUT, KW				=	17002		
CURRENT DENSITY, AMPS/M^2	=	0.12	0	FUEL CELL DC POWER, KW				=	17619		
NUMBER STACKS		70	N/A	FUEL UTILIZATION, %				=	78.0		
NUMBER CELLS/STACK	=	330	N/A	CATHODE EXIT TEMP, DEG F				=	1179.7	1180 MAX	
CELL AREA, M^2	=	7.8	N/A	CATHODE INLET TEMP, DEG F				=	1039.7	1030 MIN	
ANODE EXIT TEMP DEG C	=	1170	0	FUEL CELL OXYGEN UTILIZATION, %				=	54.5		
METHANE CONVERSION, %	=	100	N/A	FUEL CELL INLET O2 FRACTION				=	0.1232		
STACK HEAT LOSS, MBTU/HR	=	700,000	0	OUTLET O2 FRACTION				=	0.0702		
INVERTER EFFICIENCY, %	=	96.5	0	FUEL CELL INLET CO2 FRACTION				=	0.1802		
PARASITIC PWR, CONTROLS&MISC, KW	=	10	0	OUTLET CO2 FRACTION				=	0.0576		
FUEL PROCESSING				GAS TURBINE							
PREREFORM PRES, PSIA	=	18	0	TURBINE GEN NETPOWER AC, KW				=	3829		
PREREFORM INLET TEMP, C	=	752	E-3 EXIT	HI TURBINE INLET TEMPERATURE, F				=	1526		
STEAM/CH4 RATIO	=	1.5	0	LOW TURBINE INLET TEMPERATURE, F				=	1220		
INTERNAL REFORM TEMP, C	=	1075	0	HIGH TURBINE POWER, KW				=	8116		
GAS TURBINE			0	LOW TURBINE POWER, KW				=	1165		
GAS TURBINE COMP EFF, %	=	83	2	1ST STAGE COMPRESSOR WORK, KW				=	1660		
GAS TURBINE TURB EFF, %	=	83	7	2ND STAGE COMPRESSOR WORK, KW				=	1857		
GT COMPRESSOR PRESS RATIOS	=	2.47	0	3RD STAGE COMPRESSOR WORK, KW				=	1858		
EACH INTERCOOLER PRESS LOSS, PSI	=	1	0								
PRESSURE LOSS, COMP OUT TO TURB IN, PSI	=	4	0								
PRESSURE LOSS, E-9, PSI	=	1	0	PROCESS WATER TOTAL, GAL/MIN				=	16.0		
1ST TURBINE STAGE OUTLET PRESSURE, PSIA	=	22	0								
GENERATOR EFFICIENCY, %	=	98	0								
TURBINE STAGE HEAT LOSS, BTU/HR	=	10000	0								
HEAT EXCHANGER SUMMARY		REFERENCE	+/- DEVIATION	REQUIRED HEAT EXCHANGER EFFECTIVENESS							
E-1 SECOND STAGE AIR HEATER	COLD SIDE EXIT	1058	0	E-1	=		0.67				
E-2 PROCESSED FUEL REHEATER	COLD SIDE EXIT	932	0	E-2	=		0.85				
E-3 FUEL /STEAM HEATER	COLD SIDE EXIT	752	0	E-3	=		0.75				
E-4 FIRST STAGE AIR HEATER	COLD SIDE EXIT	816	0	E-4	=		0.95				
E-5 BOILER	COLD SIDE EXIT	239	0	E-5	=		0.84				
E-6 NATURAL GAS HEATER	COLD SIDE EXIT	212	0	E-6	=		0.85				
E-7 FEEDWATER HEATER	COLD SIDE EXIT	203	0	E-7	=		0.84				
E-8 TURBINE INLET HEATER	COLD SIDE EXIT	1526	0	E-8	=		0.87				
E-9 TURBINE INLET REHEATER	COLD SIDE EXIT	1220	0	E-9	=		0.83				
E-10 INTERCOOLER	EFFECTIVENES	0.762	0								
E-11 INTERCOOLER	EFFECTIVENES	0.847	0								
E-12 COOLING TOWER	EFFECTIVENES	0.811	0								

SUMMARY

HIGH EFFICIENCY POWER PLANT PROCESS SUMMARY													
PROCESS CONDITIONS													
STATION		TEMP	PRESS	ENTHALPY	COMPOSITION, VOLUME FRACTION								FLOW
NO	DESCRIPTION	DEG F	PSIA	BTU/HR	H2	H2O	CH4	CO	CO2	O2	N2	MOLES/HR	LBS/HR
1	NATURAL GAS IN	59.0	29.70	-7,949,462	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
2	DESULFUR NAT GAS	15.0	24.70	-7,949,462	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
3	HEATED NAT GAS	212.0	24.60	-7,551,780	0.0000	0.0000	0.9600	0.0000	0.0200	0.0000	0.0200	296.00	4,985
4	FUEL/STEAM/RECYCLE	233.7	19.20	-51,454,714	0.0012	0.5991	0.3835	0.0000	0.0083	0.0000	0.0080	752.02	13,187
5	PREREFORMER INLET	752.0	19.00	-47,683,213	0.0012	0.5991	0.3835	0.0000	0.0083	0.0000	0.0080	752.02	13,187
6	PREREFORMER EXIT	611.3	17.00	-47,682,947	0.0748	0.5448	0.3539	0.0001	0.0264	0.0000	0.0078	774.58	13,187
7	FUEL/STEAM TO E-2	611.3	16.71	-46,948,630	0.0742	0.5406	0.3511	0.0001	0.0262	0.0000	0.0077	768.57	12,984
8	FUEL/STEAM FROM E-2	932.0	16.61	-44,362,077	0.0742	0.5406	0.3511	0.0001	0.0262	0.0000	0.0077	768.57	12,984
9	FUEL TO STACK Rus	932.0	16.60	-44,362,077	0.0746	0.5357	0.3555	0.0001	0.0264	0.0000	0.0078	768.57	12,984
10	FUEL FROM Rus	1075.0	15.60	-31,993,635	0.4876	0.2223	0.1411	0.0619	0.0812	0.0000	0.0058	1020.34	12,984
11	FUEL TO ANODES	1075.0	15.60	-31,993,635	0.4876	0.2223	0.1411	0.0619	0.0812	0.0000	0.0058	1020.34	12,984
12	FUEL FROM ANODES	1170.0	15.52	-243,537,416	0.0715	0.3897	0.0000	0.0423	0.4938	0.0000	0.0027	2195.09	66,199
13	FUEL TO BURNER	1170.0	15.50	-243,537,416	0.0715	0.3897	0.0000	0.0423	0.4938	0.0000	0.0027	2195.09	66,199
14	BURNER PREMIX	1132.7	15.45	-199,328,832	0.0233	0.1338	0.0000	0.0138	0.1631	0.1395	0.5265	6730.09	196,756
15	BURNER EXHAUST	1595.2	15.35	-199,329,254	0.0000	0.1601	0.0000	0.0000	0.1802	0.1232	0.5364	6605.15	196,756
16	EXHAUST FROM E-8	1320.5	15.27	-216,142,646	0.0000	0.1601	0.0000	0.0000	0.1802	0.1232	0.5364	6605.15	196,756
17	CATHODE INLET	1039.7	15.19	-232,769,462	0.0000	0.1601	0.0000	0.0000	0.1802	0.1232	0.5364	6605.15	196,756
18	CATHODE EXHAUST	1179.7	15.11	-94,427,881	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
19	EXHAUST TO E-1	1179.7	15.15	-94,427,881	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
20	EXHAUST TO E-2	988.6	15.05	-102,787,402	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
21	EXHAUST TO E-3	928.4	15.00	-105,373,954	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
22	EXHAUST TO E-4	839.8	14.95	-109,145,455	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
23	EXHAUST TO E-5	440.0	14.85	-125,570,577	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
24	EXHAUST TO E-6	239.9	14.80	-133,465,280	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
25	EXHAUST TO E-7	229.7	14.75	-133,862,962	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
26	EXHAUST FROM SYSTEM	200.1	14.70	-135,014,769	0.0000	0.2005	0.0000	0.0000	0.0576	0.0702	0.6717	5274.99	143,540
27	PROCESS AIR IN	59.0	14.70	9,406,254	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
28	1ST STAGE COMP IN	59.0	14.60	9,406,254	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
29	1ST STAGE COMP OUT	237.3	36.06	15,071,344	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
30	2ND STAGE COMP IN	120.5	35.06	11,355,760	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
31	2ND STAGE COMP OUT	319.2	86.60	17,693,687	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
32	3RD STAGE COMP IN	120.0	85.60	11,339,839	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
33	3RD STAGE COMP OUT	318.7	211.44	17,679,780	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
34	PREHEATER E-4 OUT	816.0	210.11	34,104,882	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
35	PREHEATER E-1 OUT	1058.0	208.77	42,464,403	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
36	1ST TURBINE IN	1526.0	207.44	59,277,795	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
37	1ST TURBINE OUT	741.1	22.00	31,567,508	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
38	2ND TURBINE IN	1220.0	21.00	48,194,324	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556
39	2ND TURBINE OUT	1107.6	15.50	44,208,207	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800	4,535.00	130,556

SUMMARY

3/4/99 10:39		HIGH EFFICIENCY POWER PLANT PROCESS SUMMARY												
		PROCESS CONDITIONS												
		CASE		2										
STATION		TEMP	PRESS	ENTHALPY	COMPOSITION, VOLUME FRACTION								FLOW	FLOW
NO	DESCRIPTION	DEG F	PSIA	BTU/HR	H2	H2O	CH4	CO	CO2	O2	N2		MOLES/HR	LBS/HR
40	PROCESS WATER IN	59.0	30	-52,214,531	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		444.00	7,999
41	TREATED WATER	59.0	24	-52,214,531	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		444.00	7,999
42	FEEDWATER HTR OUT	203.0	23	-51,062,724	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		444.00	7,999
43	STEAM FROM BOILER	239.0	22	-43,167,937	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		444.00	7,999
44	STEAM TO EJECTOR	239.0	21.5	-43,167,937	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		444.00	7,999
45	FUEL RECYCLE	611.3	17	-734,257	0.0742	0.5407	0.3512	0.0000	0.0262	0.0000	0.0077		12.02	203
46	STEAM/ RECYCLE MIX	250.0	19.5	-43,902,543	0.0020	0.9879	0.0093	0.0000	0.0007	0.0000	0.0002		456.02	8,202
47	COOLING PMP INLET	84.0	29	-609,175,648	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		5200.00	93,683
48	COOLING PMP EXIT	84.0	36	-609,175,648	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		5,200.00	93,683
49	COOLANT TO E-10	84.0	36	-234,298,326	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		2000.00	36,032
50	COOLANT FROM E-10	187.2	34	-230,582,742	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		2000.00	36,032
51	COOLANT TO E-11	84.0	36	-374,877,322	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		3200.00	57,651
52	COOLANT FROM E-11	194.3	34	-368,523,474	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		3200.00	57,651
53	COOLANT TO E-12	191.5	34	-599,106,027	0.0000	1.0000	0.0000	0.0000	0.0000	0.0000	0.0000		5200.00	93,683
54	AIR TO TOWER	59.0	14.7	31,112,195	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800		14999.99	431,830
55	AIR FROM TOWER	155.0	14.7	41,181,817	0.0000	0.0100	0.0000	0.0000	0.0030	0.2070	0.7800		14999.99	431,830
HEAT & MASS BALANCE AROUND THE ENTIRE PLANT														
SYSTEM ENERGY AND MOLE BALANCE														
STATION		ENERGY		MASS, LB/HR		MOLES								
		BTU/HR				H2	O2	C	N2					
IN	FUEL IN	1	-7,949,462	4,985		568.3	5.9	290.1	5.9					
	PROCESS AIR IN	27	9,406,254	130,556		45.3	975.0	13.6	3537.3					
	WATER IN	40	-52,214,531	7,999		444.0	222.0	0.0	0.0					
	COOLING AIR IN	54	31,112,195	431,830		150.0	3225.0	45.0	11700.0					
	TOTAL		-19,645,544	575,370		1207.7	4427.9	348.7	15243.2					
OUT	FUEL CELL DC POWER		60,133,647											
	EXHAUST	26	-135,014,769	143,540		1057.7	1202.9	303.7	3543.2					
	COOLING AIR OUT	55	41,181,817	431,830		150.0	3225.0	45.0	11700.0					
	GT POWER		13,333,550			1207.7	4427.9	348.7	15243.2					
	GT HEAT LOSS		20,000											
	STACK HEAT LOSS		700,000											
	TOTAL		-19,645,755	575,370										
	ERROR (IN-OUT)		211	0		0.0	0.0	0.0	0.0					
	(IN-OUT)/ IN , %													