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RELATION BETWEEN COMPONENT TECHNICAL PARAMETERS
AND FUEL CELL POWER PLANT CHARACTERISTICS

Final Technical Report

By
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Work Performed Under Contract No. AC03-78ET12445

United Technologies
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U. S. DEPARTMENT OF ENERGY

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PARAMETERS AND FUEL CELL POWER PLANT CHARACTERISTICS

FINAL TECHNICAL REPORT

FCR-1737

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SUMMARY

The purpose of this study is to determine the impact of applied technology improvements on fuel cell power plant operational and cost characteristics. The results of this evaluation are intended to identify to DOE those areas which will provide the most significant payoff for long range research and development activities.

The study is focused on the phosphoric acid fuel cell and investigates both small multi-kilowatt on-site power plants as well as large multi-megawatt systems intended for dispersed utility application. In addition, since complete power plants are considered, the potential improvements in major ancillary subsystems, such as fuel processing and power conditioning, are evaluated in terms of their impact on the entire system and its potential for meeting the requirements of various applications.

It should be emphasized that the potential improvements discussed in this study are rather fundamental in nature and thus the benefits in terms of parameters such as cost, weight and maintenance savings are limited to these areas. In developing a power plant, however, there are a number of other possible improvements including items such as more efficient manufacturing and assembly techniques as well as design, control and instrumentation simplifications. These engineering areas can result in significant power plant improvements and in some cases provide even more substantial benefits than the fundamental R&D activities discussed in this report.

In performing this study it became clear that there were a number of generic improvements which, if accomplished, could benefit all of the power systems studied, some of the more significant of which are listed in Table 1. In other areas, improvements are rather specific so that they impacted primarily either the small or large power plant; these are shown in Table 2.

The body of this report discusses a large number of potential component or configuration changes. In some cases these changes were beneficial and they are

quantitatively discussed in later paragraphs of this summary. In other cases, the changes did not result in any benefits, and these are included in the body of the report for the purpose of documenting the reasons why they were not attractive. In addition, quite often improvements in specific components, which may have significant impact on the individual component itself, will have a much lesser effect on the entire system. It is therefore necessary to view improvements cumulatively in order to get a realistic appraisal of what might be achieved by R&D activities. Of course, in looking at the cumulative effects the nearer term achievements must be considered first while the longer term and thus more difficult improvements must be evaluated separately.

TABLE 1. GENERIC IMPROVEMENTS

SUBSYSTEM	COMPONENT	IMPROVEMENT	BENEFITS
FUEL CELL	CATHODE CATALYST	o HIGHER ACTIVITY	o LOWER COST
		o REDUCED NOBLE METAL USAGE	o INCREASED ENDURANCE
		o HIGHER TEMPERATURE WITH STRUCTURAL STABILITY	
	ELECTROLYTE	o REDUCED ELECTROLYTE LOSS o LOWER CORROSION	INCREASED ENDURANCE
	ANODE CATALYST	o IMPROVED TOLERANCE TO PRESENT CONTAMINANTS, E.G. H ₂ S, HALOGENS	SIMPLIFIED FUEL PROCESSING SYSTEM
FUEL PROCESSOR	REFORMER AND SHIFT CONVERTER CATALYSTS	o IMPROVED TOLERANCE TO PRESENT CONTAMINANTS, E.G. O ₂ , OLEFINS, SULFUR, HALOGENS	o SIMPLIFIED FUEL PROCESSING SYSTEM
		o INHIBITION TO CARBON FORMATION	o WIDER FUEL FLEXIBILITY
	SULFUR ABSORBENT	o REGENERABLE SYSTEM	o LOWER MAINTENANCE
AUXILIARIES	ELIMINATION OR REDUCTION OF WATER TREATMENT	o FUEL PROCESSING CATALYSTS TOLERANT TO CONTAMINANTS	o LOWER COST
		o CORROSION RESISTANT FUEL CELL COOLING SYSTEM	o LOWER MAINTENANCE

TABLE 2. SPECIFIC POWER PLANT IMPROVEMENTS

POWER PLANT CONFIGURATION	IMPROVEMENT	BENEFIT
MULTI-KILOWATT	TRANSISTORIZED INVERTER	o LOWER COST
MULTI-MEGAWATT	HIGHER PRESSURE OPERATION	o LOWER COST
		o LARGER SHOP FABRICATED MODULES
	ADVANCED FUEL PROCESSOR	o HEAVY FUEL CAPABILITY

Multi Kilowatt Power Plant

The multi-kilowatt on-site power plant studies were based on the 40 kilowatt system presently being developed at UTC under contract with the Department of Energy and the Gas Research Institute. Consideration was given to each of the major components and to the effects of changes in important performance parameters. As indicated earlier, these effects were evaluated at the power plant level and thus results were based on the interacting effects of components within the system. Table 3 lists those applied technology areas which are considered relatively near term and which impact substantially upon the entire power plant.

As indicated in Table 3 a cost reduction of 20% may be anticipated along with a substantial weight savings of 16%. The cost reduction is assessed from the base-line value used for the 40 KW power plant assuming large manufacturing production quantities.

TABLE 3. TECHNOLOGY AREAS HAVING NEAR TERM PROBABILITY OF SUCCESS

TECHNOLOGY AREA	COST	PERCENT REDUCTION	WEIGHT
o DOUBLE PRESENT CATHODE ACTIVITY	9		9.2
o 400°F CELL TEMPERATURE	6		5.5
o 93% EFFICIENT INVERTER	9		8.2
o ELIMINATION OF HYDROGENERATOR	4		.4
TOTAL	20*		15.8*

*NOT ADDITIVE

It can be seen that two of the areas open for improvement are related to the fuel cell stacks, i.e., cathode catalyst activity and higher cell temperature. The cell stack is an important area for technology R&D since it presently represents nearly 40% of the total cost of the power plant. Other improvements likely in the near term are an advanced inverter, in which transistorized circuits will yield

higher efficiency, and the elimination of the hydrogenator in the fuel preprocessing subsystem, which reduces the olefin content of the fuel entering the reformer. To accomplish each of these goals will require substantial development activity, and this is elaborated upon in Section 2 of this report. In the longer term, further improvements are projected which will result in a total cost savings for the power plant of from 30-33% as indicated in Table 4. In addition, dramatic improvements can be made in system simplification by the elimination of a large number of components presently in the system.

TABLE 4. POTENTIAL LONG TERM IMPACT OF APPLIED TECHNOLOGY ACTIVITIES

o	3-4 TIME PRESENT CATHODE ACTIVITY (OR EQUIVALENT)
o	425-450°F CELL TEMPERATURE
o	REDUCTION IN CELL DEGRADATION (1/4 - 1/2 PRESENT RATE)
o	95% INVERTER EFFICIENCY
o	ELIMINATION OF REFORMER PREPROCESSING COMPONENTS
o	ELIMINATION (OR SUBSTANTIAL REDUCTION) OF WATER TREATMENT SUBSYSTEM
PERCENT REDUCTION	
o	COST ~30-33
o	WEIGHT ~26-28

To achieve these goals, however, will require better cathode catalyst materials; a substantial increase in cell operating temperature, a reduction in cell degradation rate, a further increase in inverter efficiency, elimination of all the reformer preprocessing components, and either elimination or substantial reduction in the water treatment subsystem.

Multi-Megawatt Power Plant

In studying the impact of applied technology on the multi-megawatt acid fuel cell, it became obvious that most of the improvements described above would also be

beneficial to the larger power plant and, for the most part, the only thing to be gained by repeating a similar study would be to document the magnitude of each of these improvements on the larger system. For this reason, it was agreed with DOE that two new areas would be studied for the larger power plant; these were operation at elevated pressure and advanced techniques for handling heavier liquid fuels.

The 4.8 MW dc (4.5 MW ac) power plant presently being developed at UTC is very similar in functional operation to the 40 KW power plant described in the previous paragraphs, the major difference being that it operates at a reactant pressure level of 50 psia and can utilize a light distillate fuel. It was found in the initial optimization of this system that adding additional complexity to operate above atmospheric pressure would be cost effective in the larger sizes. The question addressed in this study was whether a further increase in system pressure is warranted.

Table 5 describes in a qualitative manner the influence of increasing pressure on the cost of the major components in the power plant. It can be seen that while about half of the components become lower in cost, the other half either increase in cost or are unchanged.

Quantitatively, for the most part, the cost reductions are substantially greater than the cost increases. Higher pressures tend to increase most catalyst activities, improve fuel cell performance, increase heat transfer characteristics and raise the temperature required to accomplish water recovery. The major technical factors (both pro and con) of increasing system pressure are summarized in Tables 6 and 7, and are discussed in detail in Section 3 of this report.

TABLE 5. IMPACT OF PRESSURE ON THE COST OF MAJOR COMPONENTS
(CONSTANT RATING)

	COMPONENT	EFFECT OF INCREASING PRESSURE ON COST
+ REDUCED COST	HYDRODESULFURIZER	+
	SULFUR ABSORBER (ZNO)	-
	REFORMER- BURNER	-
- INCREASED COST	SHIFT CONVERTERS	+
0 NO CHANGE	FUEL CELL	+
	TURBOCOMPRESSOR	-
	HEAT EXCHANGERS	+
	COOLING TOWERS	+
	WATER TREATMENT	0

TABLE 6. MAJOR TECHNICAL FACTORS AFFECTING COMPONENTS
FUEL PROCESSING SUBSYSTEM

COMPONENT	MAJOR TECHNICAL FACTORS* INFLUENCED BY PRESSURE	
HYDRODESULFURIZER	o	HIGHER CATALYST ACTIVITY
	o	INCREASED LIFE FROM LOWER CARBON DEPOSITION
SULFUR ABSORBER	o	NO ANTICIPATED CHANGE IN ABSORBER CHARACTERISTICS
REFORMER-BURNER	o	REDUCED FUEL CONVERSION
	o	IMPROVED HEAT TRANSFER
SHIFT CONVERTER	o	HIGHER CATALYST ACTIVITY

*FOR MANY COMPONENTS HIGHER PRESSURES REQUIRE THICKER PRESSURE VESSELS - HOWEVER, IN SOME CASES THE VESSEL SIZE IS REDUCED AND THUS EFFECT ON COST WILL VARY WITH SPECIFIC COMPONENTS.

TABLE 7. MAJOR TECHNICAL FACTORS AFFECTING COMPONENTS
FUEL CELL SUBSYSTEM

COMPONENT		MAJOR TECHNICAL FACTORS INFLUENCED BY PRESSURE
FUEL CELL	o	HIGHER THERMODYNAMIC POTENTIAL
	o	LOWER CATHODE POLARIZATION
	o	INCREASED MATERIAL CORROSION
	o	LOWER ACID LOSS
TURBO-COMPRESSOR	o	MAINTENANCE OF HIGH EFFICIENCY REQUIRES MULTI STAGES OR ALTERNATE DESIGN CONCEPTS
HEAT EXCHANGERS AND CONDENSERS	o	IMPROVED HEAT TRANSFER
	o	HIGHER CONDENSING TEMPERATURE
COOLING TOWERS	o	HIGHER CONDENSING TEMPERATURES ALLOW LARGER ΔT BETWEEN LIQUID COOLANT AND COOLING AIR
WATER TREATMENT	o	NO APPRECIABLE CHANGES ANTICIPATED

The overall results of the system pressure study are shown in Figure 1, which defines the relative cost of an entire power plant as a function of pressure (taken as the reactant pressure at the fuel cell stack). The circled point represents the reference case at 50 psia and is based on costs for a mature technology (large production quantities). It can be seen that increasing pressure at a given power plant size of 4.5 MW reduces system cost by about 10%, and above 120-150 psia the gains are not substantial. A more dramatic effect of going to higher pressure, however, is the ability to construct a larger (10 MW) power plant. This can be done while maintaining the maximum module size for factory construction and assembly and the flexibility of transporting the plant to any site in a modular fashion on trucks. As shown in the figure, this not only tends to reduce the cost because of the higher pressure but also has the beneficial effect of reducing costs due to the scale effect. For example, relatively fixed cost items such as control, instrumentation, etc. tend to have a less significant effect on overall costs. Thus, designing a 10 MW power plant at 120 psia results in a cost savings over the reference 4.5 MW, 50 psia system of about 22%. In addition, studies indicate the larger size higher pressure system can be operated at a lower rated power heat rate of 8500 BTU/ KW-HR without a substantial cost penalty.

Figure 1. Resultant System Cost vs. Pressure

As mentioned above, the multi-megawatt power plant was studied to evaluate the influence of operating with heavier fuels, i.e. fuels heavier than light naphtha or natural gas. Three potential fuel processing systems were considered: an auto-thermal reformer (ATR), a "hybrid" system utilizing a thermal steam reformer in conjunction with an ATR, and a third option, which uses a dual-cyclic-reforming bed in which process gas is made in one unit while the second unit is being regenerated. All of these systems involve the use of advanced catalysts which must be capable of operating in the presence of sulfur, unsaturated hydrocarbons and in some cases, oxygen, while still providing high fuel conversion and reasonable life between catalyst charge replacements.

As discussed in more detail in Section 3.4, a major technology activity is required to ensure the development of specific catalysts for each system. In addition, since some of the systems operate at relatively high temperature, significant benefits can be gained by developing improved materials which are structurally sound in the required environment and yet are lower in cost. For some of the

systems there is a need for high temperature heat exchangers. Development of improved materials as well as configurations favoring high heat transfer rates would be especially beneficial for these requirements.

Figure 2 describes the projected relative cost on a power plant basis of the three systems capable of handling heavy fuels compared to the reference steam-reformer fuel processor system which operates only on naphtha or natural gas. The data is presented at a constant rated power plant heat rate of 9300 BTU/KW-HR. The projected costs of the advanced concepts vary from 20% higher than the baseline system to about 6% below this cost. The technology level for each of these concepts is in its very early stages, and it is difficult to make a specific selection based on presently available data. Significant technology advancements must be made, and these requirements are discussed further in Section 3.4.

Figure 2. Baseline Systems Economic Comparison

1 PROGRAM OBJECTIVES AND SCOPE

1.1 OBJECTIVES

The primary objective of this study is to determine the impact of technology improvements on overall fuel cell power plant characteristics. Wherever possible this is done on a quantitative basis so that emphasis can be placed on technology activities which have the greatest improvement potential. These results are available to DOE for use in defining an organized R&D program in which specific tasks and goals can be defined for various power plant components.

The study uses power plant configurations presently under development at UTC as reference systems from which to investigate the effects of technology improvements. Alternate configurations are also studied to evaluate the potential benefits of these concepts and to identify the technology levels of unique components required to make these systems economically viable.

1.2 SCOPE

The program is focused on systems using the phosphoric acid fuel cell. Both a multi-kilowatt and a multi-megawatt power plant are studied. The multi-kilowatt power plant is intended for on-site use in commercial and industrial applications while the large power plant may be used for electric utility and industrial applications. There are a number of functionally similar components in each of these systems. For this reason the smaller power plant is studied in detail on a component level with many of the conclusions being also applicable for the larger system. For the multi-megawatt power plant, emphasis is placed on determining the influence of higher operating pressures and on schemes for processing heavier hydrocarbon fuels.

1.3 APPROACH

The general approach to the study is first to establish overall reference power plant configurations based on present technology levels. Performance and economic characteristics are then defined with the economic characteristics based on the large production quantities typical of a mature commercial market.

For each of the reference systems, selected components are identified which most influence the performance and cost of the entire power plant. For these components, key variables are identified and limiting phenomena established. Assumptions are made as to the range of potential improvements that could be made for these key variables and evaluations are then made as to the effect on a total power plant level. In some cases, the same process is accomplished based on an alternate configuration - but again, the results are brought to a power plant level so that the impact of specific changes can be properly evaluated on a quantitative basis.

1.4 EVALUATION CRITERIA

The effect of technology improvements is measured against a specific set of evaluation criteria. The primary factor is the influence of a specific technology change on capital cost. Quite often a change in the performance of one component, which may lower its individual cost, will influence other portions of the power plant and may result in a negative effect on the total power plant cost.

Another important evaluation criteria used is performance as specifically defined by efficiency both at rated and part power operation.

Component life is also used as a consideration in the various system studies. The need for component replacement establishes maintenance costs and influences power plant availability.

To a lesser extent, and primarily for the multi-kilowatt power plant, weight, volume and footprint were considered in the evaluation process.

2 MULTI-KILOWATT POWER PLANT

2.1 40KW POWER PLANT CHARACTERISTICS

The on-site power plant presently being developed at UTC is designed to produce 40 KW at rated power with a potential overload of 40% for five seconds to handle surges associated with motor starting. The system is designed to utilize either natural gas or peak shaved gas and is capable of operating at 40% efficiency between rated and 50% power.

Electrical power is delivered as 3 phase 60 HZ alternating current at 120/208 volts. Frequency stability is $\pm .0002$ percent per year for proper operation of clocks. Steady state output of any phase is 120 volts $\pm 5\%$ from minimum to rated power output conditions, including load unbalance conditions between phases of up to 30%.

Water recovery equipment is included with the power plant so that no external water supply is required for process purposes. The power plant is air cooled, so no water is required for cooling.

The power plant can be started-up in four hours from cold condition with operation being automatic. Load response is instantaneous. During startup, however, external electricity must be supplied to provide power for electric heaters, pumps and control components.

The power plant may be installed as a single unit or multiple units up to six. For multiple power plant installations a master control unit is utilized for coordinating parallel operation.

2.2 SYSTEM DESCRIPTION

The system, which operates at approximately atmospheric pressure, is shown schematically in Figure 2-1. Fuel enters the preprocessor subsystem where it is mixed

with a portion of recycled fuel gas that has already been processed. This mixture then flows through a preoxidizer where oxygen is removed, if it is present, in a peak shaved fuel. The fuel stream then enters the hydrodesulfurizer where sulfur in the fuel is converted to hydrogen sulfide (H_2S) which is then chemically absorbed by a zinc oxide bed. The effluent clean gas is then passed over a hydrogenator which is intended to saturate remaining olefins and reduce these compounds to prevent fuel cracking.

Figure 2-1. 40-kW Power Plant Schematic

The desulfurized fuel is mixed with steam and enters the fuel processing subsystem where they are catalytically converted into a hydrogen-rich gas after passing over both reform and shift converter catalysts. The hydrogen-rich gas, cooled and filtered, flows to the power section.

The power section electrochemically consumes hydrogen which is reacted with oxygen from the process air system to produce direct current electricity. Water is pro-

duced as a by-product of the electrochemical process. The depleted fuel gas stream leaves the power section and flows to the reformer burner where the remaining fuel is consumed with air from the process air system to produce the thermal energy required for the steam reforming process. Reformer burner exhaust combines with depleted air from the power section and flows to the condensers to be cooled for water recovery. The water is subsequently used for fuel processing after being cleaned up in the water purification subsystem which contains demineralizing beds and filters.

The thermal management subsystem controls power section temperature by circulating water through the cell stacks. In the power section, waste heat generated in the process of producing power is removed by changing the circulating water into a two phase mixture of steam and water. Steam is separated for use in the fuel processing subsystem. The remaining water is collected, purified and recycled through the coolant loop.

DC power from the power section is fed to the inverter assembly which converts the unregulated dc output power into voltage-regulated, current-limited ac power with fault clearing capability.

2.3 PERFORMANCE CHARACTERISTICS

The 40 kW power plant efficiency as a function of the percent of rated power is shown in Figure 2-2. It can be seen that the efficiency characteristic is constant between rated and 50% of power. Below this point the efficiency drops off due to heat loss and higher mechanical and electronic losses.

The power plant is designed so that waste heat may be recovered for external use. High grade heat is recovered by directing the cell coolant to the high grade heat exchanger where 15 to 60 psig steam is produced. Low grade heat is recovered by passing the power section and fuel processing exhausts through a heat exchanger which provides 160°F hot water. Available waste heat as a function of power level is shown in Figure 2-3.

Figure 2-2. 40-kW Power Plant Performance Characteristics

Figure 2-3. High Grade/Low Grade Heat Availability

2.4 COST AND PHYSICAL CHARACTERISTICS

Figure 2-4 illustrates the relative costs associated with the major power plant subsystems. As shown, the fuel cell stack and fuel processing and clean-up subsystems represent 60% of the total power plant cost. Emphasis for this study has been placed on improvements in these areas.

Figure 2-4. 40-kW Power Plant Cost Characteristics

58-39

Power plant physical characteristics are shown in Figure 2-5. The projected overall dimensions for the 40 KW reference system are illustrated in the figure and result in a specific volume of $7.6 \text{ ft}^3/\text{KW}$ and a specific weight of $175 \text{ lbs}/\text{KW}$ and a maximum floor loading of $150 \text{ lbs}/\text{ft}^2$ on a 47 ft^2 footprint.

(WCN-6188)

- PASSAGE THROUGH STANDARD 6'8" HIGH DOUBLE DOOR
- DRY WEIGHT 7000 LBS

Figure 2-5. Power Plant Physical Characteristics

2.5 CANDIDATE COMPONENTS FOR TECHNOLOGY IMPROVEMENTS

As discussed above, the subsystems which contribute most heavily to the overall power plant costs are the cell stack, the fuel processing and clean-up section and the power conditioning equipment (primarily the dc to ac inverter). The following

topics in this portion of the report describe what overall power plant benefits can be derived from specific technology improvements in the components listed in Table 2-1.

Table 2-1.

CANDIDATE COMPONENTS FOR TECHNOLOGY IMPROVEMENTS

CELL STACKS

FUEL PROCESSING & CLEAN-UP

- . REFORMER
- . SHIFT CONVERTER
- . PREOXIDIZER
- . HYDRODESULFURIZER
- . ZINC OXIDE ABSORBER
- . HYDRO TREATER

PROCESS WATER

- . ION EXCHANGE RESIN

POWER CONDITIONING

- . INVERTER SWITCHING DEVICES
-
-

2.6 CELL STACK

2.6.1 Cell Stack Description

The cell stack consists of a large number of individual cells electrically connected in series. As shown in Figure 2-6, each cell contains two platinum catalyzed

electrodes (anode and cathode) separated by a porous matrix containing concentrated phosphoric acid electrolyte. The carbon electrode support is ribbed so that a cavity is formed at each electrode to permit the passage of reactant gases and also to allow the transport of electric current. Hydrogen is consumed at the anode and combines with oxygen at the cathode to produce dc electricity, product water and some waste heat. The waste heat is caused by inefficiencies at the electrodes and ohmic losses. The overall reaction may be described as follows:

Figure 2-6. Power Section Cell Stack

As shown in the figure, coolers located within the stack remove the heat by the vaporization of water. The water flows through small diameter tubes located between groups of cells. The tubes are coated to protect them from the cell environment. This method of cooling insures that uniform temperatures are maintained throughout the stack.

During operation there is a small evaporative loss of electrolyte which is carried out by the vented gases. To compensate for this loss, the anode material is filled with excess electrolyte.

Product water is carried out with the cathode vent gas and is subsequently condensed and reused in the system.

The reference 40 KW power plant contains a single stack containing 270 cells, each cell having an active area of about 2.2 square feet. Coolers are located every six cells. Total stack height with support structure is 67 inches.

2.6.2 Impact of Improved Cathode Catalyst Activity

Figure 2-7 is a qualitative representation of fuel cell performance, showing that the major efficiency loss occurs at the cathode. In particular, this loss can be identified with polarizations associated with catalyst activity. In the baseline cell design the platinum catalyst itself represents a major fraction of the manufactured cost of the stacks. It is therefore of interest to investigate the impact on the total power plant of improving the cathode catalyst activity and/or the potential of reducing the amount of catalyst used.

Figure 2-7.
Cathode Catalyst Activity

Increased activity will result in higher cell power density allowing the use of smaller cells and stacks. Present test cells using advanced catalyst formulations have already achieved a factor of two improvements over the activity value used as the baseline for this study. In addition optimization of these catalyst structures and increase in surface area could yield significant further improvements. The effect of reduced stack size will require modifications in both cooler design and anode thickness to maintain proper operating temperatures and adequate electrolyte inventory.

The resulting effect of increased cathode activity on overall power plant cost is shown in Figure 2-8. The upper solid curve shows the percent reduction in cost with electrolyte loss as presently measured. The dashed curve shows the cost reduction if electrolyte loss were completely eliminated.

Figure 2-8. Cathode Activity Increase vs. System Cost

Clearly, improvement in cathode activity is a primary technology goal since it influences total cost substantially. As will become obvious in the following sections, it is difficult to find a single factor, which, if improved, could have a 10% or greater impact on power plant cost. Advanced cells being tested in the laboratory have shown activity increases of 100%, and there is no reason to believe that this is a limit.

Alternately, improved cell performance due to higher cathode activity can also be used to improve system efficiency. This trend is shown in Figure 2-9. The fuel cell stack may be operated at higher cell voltage, rather than higher power density. This will yield improved fuel cell efficiency and as shown in the figure will also increase system efficiency. An increase in cathode activity by a factor of 2 will result in a system efficiency improvement of about 2 percentage points.

Figure 2-9. Cathode Activity Increase vs. System Efficiency

2.6.3 Impact of Improved Carbon Monoxide Tolerance

Carbon monoxide (CO), which in general lowers performance, enters the fuel cell at a concentration of about 0.6% on a dry gas basis. Studies conducted during this program have shown that the effect of this level of CO on cell performance at the

operating temperature of 375°F is very small. This result is also true if the cell performance is substantially improved due to higher cathode activity. Thus a program to improve the tolerance of the anode to the effects of CO would not result in an overall system benefit.

2.6.4 Impact of Increased Cell Temperature

Another approach for increasing cell performance is to operate at higher temperatures. This has the same effect on cell performance as increasing the activity of the catalyst.

Higher temperature, however, can cause increased electrolyte loss which, if not compensated for, will shorten the useful life of the cell. In the UTC design electrolyte may be stored in the cell in sufficient quantity to insure proper design life for temperatures of 375°F and probably somewhat higher. At significantly higher temperatures, an alternate solution must be found. In larger power plants increasing reactant pressure, as discussed in Section 3, is a viable solution. For the smaller atmospheric reactant pressure power plant design, several alternate concepts have been suggested, and some have even undergone testing; however, no long term solution has yet been verified. This represents another area where technology activities could have substantial payoff.

Figure 2-10 illustrates the maximum reduction in system cost which could be realized at increasing temperatures. This benefit, which is substantial, is based on the assumption that the acid inventory within the cell can be maintained relatively constant.

Figure 2-10. System Cost vs. Average Cell Temperature

2.6.5 Impact of Utilizing Lower Cost Cell Materials

As pointed out earlier, the fuel cell electrode catalyst represents a substantial portion of the total stack cost. The platinum catalyst fluctuates in its cost depending on the supply and demand characteristics throughout the world at any point in time. Figure 2-11 shows the sensitivity of the overall power plant to the cost of platinum. The effect of these fluctuations can be significant and points out the desirability of increasing catalyst activity or reducing catalyst loadings (Mg/Cm^2) on the cell. An alternate solution is to develop a substitute catalyst material which is lower in cost and which has characteristics of performance and materials compatability similar to that of platinum.

Figure 2-11. System Cost vs. Catalyst Cost

2.6.6 Impact of Varying Reactant Gas Utilizations

One of the parameters studied under this program is the influence of increasing oxygen utilization. In doing this several factors must be considered. Higher oxygen utilizations tend to reduce cell performance and thus increase cell stack cost. At the same time, however, the air blower can be smaller, the parasite power associated with the air feed system is reduced, the condenser for removing product water from the depleted air stream can be made smaller, and the acid vapor loss from the stacks is lowered - all factors which favor an increase in utilization. Study results indicate that increasing the utilization above the 50% value used in the reference system is not beneficial.

A similar study was done for hydrogen utilization to see if system efficiency could be increased. It was found, however, that if the utilization of hydrogen was increased only a small amount above the 80% used in the reference system, a heat transfer limit would be reached in the reformer - thus making this approach impractical.

2.6.7 Impact of Reducing Cell Degradation Rates

Fuel cell stack performance does not remain constant as a function of operating hours; there is a slow performance loss due to a variety of factors. These include slow changes in the catalyst structure, some loss of the cathode catalyst due to oxidation and dissolution in the electrolyte, corrosion of the catalyst support material, and small amounts of electrolyte loss. The power plant is designed so that the anticipated degradation is accounted for and thus after 40,000 hours the system can not only deliver rated power, but is also capable of achieving the 40% overload requirement without exceeding the lowest voltage limit allowed by the inverter.

If this degradation could be eliminated or the rate reduced, there would be a significant impact on the power plant cost. This would allow the fuel cells to be designed at higher power densities (lower cost) while still maintaining the desired efficiency. This is certainly a fruitful area for applied research activities and is considered a major item in the list of potential improvements that can be gained in the long term.

2.7 FUEL PROCESSING AND CLEAN-UP SUBSYSTEM

2.7.1 Reformer Description

In the reformer, natural gas and steam are reacted over a nickel catalyst to produce a hydrogen-rich product gas. The heat for this reaction is supplied by burning the fuel cell anode exhaust, which contains some residual hydrogen, carbon monoxide and methane.

Physically, the reformer is composed of a number of tubes in which the catalyst is placed in an annular space adjacent to the outer tube wall. The burners, which are located above the tubes, fire downward. The burner cavity is partially filled with inert packing material to enhance heat transfer. The outer reformer walls are internally insulated to permit the use of low cost materials.

2.7.2. Impact of Improvements in Reformer Catalyst Activity

The reformer catalyst, when fresh, is limited in the rate of fuel reaction at low temperatures. The catalyst also tends to degrade with time due to a number of processes such as sintering (loss of area), carbon formation caused by the cracking of olefinic compounds, and sulfur poisoning caused by any residual sulfur that may pass through the desulfurizer. A study was made to evaluate the improvement that may be gained by improving catalyst activity. Results indicated that a factor of 5 improvement in activity which has been demonstrated on advanced catalysts, would reduce system cost by only 0.5%. Increasing the tolerance of the catalyst, however, could increase useful life and therefore reduce maintenance requirement.

2.7.3. Shift Converter Description

The function of the shift converter is to increase the hydrogen content of the process gas stream by promoting the following reaction:

The shift converter not only enriches the process gas in hydrogen but also reduces the concentration of carbon monoxide (CO), which tends to reduce cell performance. The process is carried out over a catalytic bed and is favored thermodynamically by low temperature and is independent of pressure. However, both higher pressure and temperature improve the kinetics of the reaction. The catalyst is constrained to operate between 375 and 550°F and is designed to effect a sufficient conversion so that the maximum CO going to the cells will be below acceptable levels.

2.7.4. Impact of Improved Shift Converter Catalyst Activity

A study was conducted to establish the impact of improved activity of the shift catalyst. The result was similar to that found for the reformer. An assumed five-fold increase in activity will only reduce system cost by 1.0%. The shift catalyst, however, is sensitive to impurities in the incoming process gas. Trace

constituents such as sulfur, chlorine or olefins (ethylene, propylene) will cause a loss of catalyst effectiveness. Also, operation of the catalyst at high temperatures will cause sintering, resulting in reduced surface area and lower performance.

It therefore appears that higher catalyst activity is not a high payoff area but that increased shift-converter catalyst tolerance to impurities is beneficial, especially if the tolerance of the reformer catalyst can be improved as well.

2.7.5 Impact of Elimination of the Shift Converter

The power plant was studied to assess the impact of eliminating the shift converter. There are two major effects when the shift converter is removed. The CO level entering the cell increases by a factor of 17, and the utilization of hydrogen in the cell must increase substantially in order to maintain a constant system efficiency. Both of these factors tend to decrease cell performance. Results indicate that the cost gain made by eliminating the shift converter and associated equipment is outweighed by the increased cost of the fuel cell stack so that the net system cost is increased by almost 4%.

It was then postulated that CO tolerant cells could be developed, and the study results were re-evaluated. It was found that the decrease in cell performance by just going to the higher hydrogen utilization resulted in a cost increase of the cells that just equalled the saving made by removal of the shift converter. Therefore, while work on CO tolerant cells could result in system simplification, very large benefits are not realized since it does not result in a positive impact on either overall cost or efficiency.

2.7.6 Description of Fuel Preprocessing Components

The fuel preprocessing subsystem consists of four major components, preoxidizer, a hydrodesulfurizer, a sulfur absorbent such as zinc oxide, and a hydrotreater. All of the components are packed beds with three of the beds containing catalysts for promoting specific reactions. The preoxidizer and hydrotreater are included for processing peak shaved gas.

The function of the preoxidizer is to consume oxygen contained in the fuel gas. If this oxygen reaches the hydrodesulfurizer or reformer catalyst, it could react with hydrogen causing an overtemperature condition and/or loss of catalyst activity.

The hydrodesulfurizer converts sulfur compounds in the incoming fuel to hydrogen sulfide (H_2S). This reaction is carried out at temperatures between 450-500°F. A typical reaction occurring in the hydrodesulfurizer is illustrated below;

where a complex hydrocarbon containing sulfur is converted to butane (C_4H_{10}) a saturated compound, and H_2S .

The sulfur absorption process takes place in a bed of pelletized zinc oxide (ZNO). The ZNO reacts with the H_2S to form zinc sulfide and water in the following proportions:

When the bed is saturated with sulfur, it is replaced by a fresh charge. The bed capacity for sulfur is estimated to be between 20 and 25% of the weight of the original charge. Exit sulfur levels in the process gas are generally below .015 ppm by volume.

The hydrogenator is used to saturate olefinic hydrocarbons before entering the reformer. This is particularly important when peak shaved gas is used in which there is frequently a small amount of propylene present. The reaction which occurs is as follows:

The propylene is converted to propane. Excessive amounts of olefinic compounds entering the reformer could cause thermal cracking. This would result in carbon formation to occur in the reformer and reduce the effectiveness of the catalyst.

2.7.7 Impact of Improved Catalyst Activity for Preprocessing Components

A parametric study was conducted to evaluate the influence of various levels of improvements in activity of the preprocessing catalysts. Figure 2-12 indicates the results of this study. Substantial increases in individual component catalyst activity has relatively small effect on total system cost. The hydrogenator is the most significant component because it employs a noble metal catalyst.

Figure 2-12. Reformer Preprocessing Components

2.7.8 Elimination of Preprocessing Components

Elimination of all or some of the preprocessing components could have an impact on the system in several aspects. Primarily, if all the components and associated controls and heat exchangers can be eliminated, a total system cost savings of 7.3% would be realized if no compensating costs are accrued. In addition, system simplification can be made, which would increase reliability and reduce maintenance costs of replacing the various preprocessing catalysts as often. Further improvements such as weight and volume reductions can be realized.

To eliminate these components, however, implies technology improvements in other areas of the power plant. Eliminating the hydrotreater requires that the reformer and shift converter catalysts be improved in their ability to process gases containing olefins of the concentration typical in peak shaved gas.

Elimination of the preoxidizer requires that the hydrodesulfurization catalyst be capable of tolerating the oxygen concentration present in peak shaved gas.

Elimination of all preprocessing components will necessitate a fuel cell tolerant to the low levels of sulfur present in natural gas, a shift catalyst tolerant to olefins and sulfur, and a reformer catalyst which can operate in the presence of olefins, sulfur and oxygen, all constituents that may be present in either the natural gas or peaked shaved gas.

2.7.9 Process Water Purification Subsystem Description

The water purification subsystem continuously processes a portion of the condensed product water to remove harmful impurities. The product water is used to generate process steam for the reformer. In addition, a portion of the water coolant system for the stacks is blown down and purified to eliminate electrically conductive materials from accumulating in the system.

The water purification subsystem includes a charcoal filter and demineralizers, which contain ion exchange resins to remove dissolved water impurities. It is essential that the water which is used for process steam be free of sulfur and halogens since these materials will degrade the reformer catalyst performance. It is also essential that the water used for cooling the stacks be low in ionic conductivity to prevent shunt current losses and material corrosion. This implies the removal of dissolved metals and other materials which may become ionized.

2.7.10 Impact of Increased Temperature Operation of Demineralizer Beds

Present demineralizer resins require that operating temperature be below 150°F for effective operation. If a higher temperature resin material could be developed

(220°F) with the same capacity, system cost could be reduced by 2.5%. The cost reduction would come from the elimination of a regenerative heat exchanger and associated equipment which is presently in the system to reduce water temperature to 150°F.

2.7.11 Impact of Elimination of Water Purification Subsystem

If the entire water treatment subsystem were eliminated, power plant cost would be reduced by about 6%. This, however, implies, as indicated above, an increased tolerance of the reformer catalyst to impurities and a cooling system which will remain corrosion resistant for long periods of time.

2.7.12 Power Conditioning Subsystem Description

The power plant electrical system is depicted in Figure 2-13.

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Figure 2-13. Simplified Electrical Diagram

The power section supplies dc voltage over a 2:1 range as a function of current level. The inverter is a three-phase solid-state switch which inverts the dc voltage and regulates the ac voltage at a nominal level of 120/208 volts ac.

Single phase, 120 volt ac is provided through use of a neutral forming auto-transformer. A portion of this power is supplied to the power plant controller serving to make the power plant electrically self-sufficient.

The inverter provides an uninterruptible power source to maintain operation of critical power plant components during fault clearing periods. The inverter also provides various ac voltages and a power section output dc current signal for use by the controller.

The power plant controller is a programmed microcomputer which provides the control intelligence for the three basic power plant operating modes: start, run and shutdown.

A master controller is used to parallel powerplants in multi-unit installations.

2.7.13 Impact of Higher Power Conditioning Efficiency

The design presently under development uses silicon controlled rectifiers (SCR's) in the inverter bridges. Utilization of transistors rather than SCR's can improve the overall system efficiency by reducing commutation losses. An increase in inverter efficiency will allow operation of the fuel cells at higher power density while overall power plant efficiency is maintained constant. Operation of the cells at higher power density has a significant impact on cost. This is illustrated in Figure 2-14 which quantitatively shows the reduction in overall power plant cost with increasing inverter efficiency. Preliminary studies indicate that this increase in inverter efficiency may be from the present 89.5% to about 93%, resulting in a cost reduction of 9%.

Figure 2-14. Power Conditioning Efficiency vs. System Cost

2.7.14 Major Conclusions of Multi-Kilowatt Power Plant Study

In the previous paragraphs, improvements in individual power plant components have been discussed. This section summarizes those results and attempts to indicate the magnitude of cumulative effects in terms of what technology improvements might be expected in the near term and what longer term activities might achieve.

Table 2-2 is a listing of the anticipated near term improvements, assuming that adequate technology funding will be available to pursue each area. There are four major areas of improvement which appear to be attainable in the near future. These are: doubling the cathode catalyst activity, increasing the operating temperature of the cells to 400°F, increasing the inverter efficiency, and eliminating the hydrogenator. The results of accomplishing these improvements would result in a 20% reduction in total power plant cost and would reduce the packaged weight by about 16%.

Table 2-2

MAJOR CONCLUSIONS
TECHNOLOGY AREAS HAVING NEAR TERM PROBABILITY OF SUCCESS

TECHNOLOGY AREA	PERCENT REDUCTION	
	COST	WEIGHT
DOUBLE PRESENT CATHODE ACTIVITY	9	9.2
400°F CELL TEMPERATURE	6	5.5
93% EFFICIENT INVERTER	9	8.2
ELIMINATION OF HYDRO- GENERATOR	4	.4
TOTAL	20*	15.8*

* NOT ADDITIVE

In the long term, as indicated by Table 2-3, it is expected that further improvements will be made in cathode activity, operation at higher cell temperature, and improved inverter efficiency. In addition, it is assumed that cell degradation rates can be reduced, additional reformer preprocessing components can be eliminated and the water treatment subsystem can be eliminated. All of this would result in a power plant cost reduction of between 30 and 33% and a weight reduction of 26-28%.

Table 2-3

MAJOR CONCLUSIONS
POTENTIAL LONG TERM IMPACT OF APPLIED TECHNOLOGY ACTIVITIES

- . 3-4 TIME PRESENT CATHODE ACTIVITY (OR EQUIVALENT)
- . 435-450°F CELL TEMPERATURE
- . REDUCTION IN CELL DEGRADATION (1/4 - 1/2 PRESENT RATE)
- . 95% INVERTER EFFICIENCY
- . ELIMINATION OF REFORMER PREPROCESSING COMPONENTS
- . ELIMINATION OF WATER TREATMENT SUBSYSTEM

PERCENT REDUCTION

- . COST 30-33
 - . WEIGHT 26-28
-

3 MULTI-MEGAWATT POWER PLANT

3.1 SCOPE OF STUDIES

The multi-megawatt phosphoric acid fuel cell is intended for electric utility or industrial use. This larger power plant has many functionally similar components with the multi-kilowatt unit. Many of the conclusions on the effects of technological improvements on system components are applicable to multi-megawatt units. For the large power plant the specific factors investigated included the influence of higher operating pressures and the development of alternate system configurations for processing heavier hydrocarbon fuels.

3.2 SYSTEM DESCRIPTION

A simplified system schematic for the pressurized multi-megawatt fuel cell is shown in Figure 3-1. Fuel entering the power plant is pumped to system pressure, vaporized and mixed with an H_2 -rich recycle stream. This mixture passes through a hydrosulfurizer which converts the fuels' sulfur compounds into hydrogen sulfide (H_2S). The H_2S is then removed by absorption on a zinc oxide bed.

Figure 3-1. Simplified System Schematic Major Components

The desulfurized fuel is then combined with steam and enters the reformer where the mixture is catalytically converted into a hydrogen-rich gas. The H_2 content of the product gas is further increased by two stages of shift conversion ($H_2O + CO \rightarrow CO_2 + H_2$). The gas is then cooled and passes into the power section (cell stacks) where hydrogen and oxygen from the process gas and air streams are electrochemically combined producing direct current electricity and by-product water. Both the air and fuel streams entering the fuel cell are pressurized. The depleted fuel gas stream leaves the power section and passes through a water recovery condenser. After the condenser it enters the reformer burner where it is combusted to provide thermal energy for the steam reforming reaction. Process air leaving the power section contains by-product water which is recovered by a condenser. The drier pressurized air is mixed with the hot, high pressure reformer burner exhaust. This combined stream is then expanded through a power recovery turbine which in turn drives the process air compressor.

Water recovered in the condensers is recycled to the thermal management subsystem. The primary function is to control the power section temperature by circulating water through the cell stacks. Waste heat generated in the process of producing power is removed by evaporating a portion of the circulating water. Steam is separated for use in the reformer. The remaining water is collected, purified and circulated through the cell stacks.

DC power from the fuel cells is converted to utility quality a.c. by a self-commutated inverter and conventional transformer.

3.3 OVERALL IMPACT OF HIGHER PRESSURE OPERATION

This study investigated the operation of a 4.5 MW fuel cell system at pressures higher than the baseline 50 psia power plant design which showed a substantial cost advantage when compared to a similar system at ambient pressure. At higher pressures the costs of the fuel cell, heat exchangers, shift converters and hydrodesulfurizer are reduced while the costs of the turbocompressor, reformer-burner, and sulfur absorber tend to increase. Figure 3-2 shows the net effect of operating pressure on system costs relative to the cost of a 4.5 MW, 50 psia baseline power

plant. The comparative cost of a 10 MW size unit is also shown. For the 4.5 MW power plant relative costs drop 8.4% at 120 psia and 11% at 200 psia. In addition, scaling up to a 10 MW unit size drops the costs an additional 13-14%.

Figure 3-2. Resultant System Cost vs. Pressure

The study shows that the operation of the fuel cell system at pressures greater than 50 psia is generally beneficial in terms of power plant cost. The lower limit on pressure is based on the largest reformer vessel which is truck transportable. This minimum pressure is somewhat below 50 psia for 4.5 MW units and 120 psia for a 10 MW power plant.

The rated power heat rate of the reference case (4.5 MW, 50 psia) is 9300 BTU/KWH. Higher heat rates increase the fuel processing costs because the lower efficiency system must process more fuel per KW of electricity produced. At the same time the fuel cell stack cost is lower because the power section can be run at higher power densities. Figure 3-3 shows that these counteracting cost factors optimize at about a 9300 heat rate for the 4.5 MW system at 50 psia operating pressure. As

shown in the same figure, operating at a pressure of 120 psia minimizes the cost penalty incurred at lower heat rates (higher system efficiencies).

Figure 3-3. Cost Variation as a Function of Heat Rate

3.3.1 Impact of Pressure on Desulfurization Subsystem

The function of the desulfurization subsystem is the conversion of sulfur compounds in the fuel to hydrogen sulfide which is subsequently removed by an absorbent. These process steps are accomplished by use of a hydrodesulfurizer (HDS) and a ZnO absorbent bed as described previously in Section 2.7.6.

The hydrodesulfurizer combines hydrogen recycled from the cell stack inlet with sulfur found in the fuel. This reaction is both thermodynamically and kinetically favored by pressure. In addition, higher pressure decreases the potential for carbon deposition which is the major decay mode of the HDS catalyst. For a 40,000 hour design life, the required catalyst volume at 200 psia is about 30% of the catalyst needed at 50 psia. Thus higher pressures significantly reduce the size

and therefore the cost of the HDS. This conclusion is based on the best presently available data; however, further technological verification on the effects of pressure, sulfur concentration, operating time, and temperature is necessary.

Removal of the H_2S is done by absorption in a bed of ZnO . The reaction is:

There is no thermodynamic benefit at higher pressures, and any enhancement to the kinetics due to pressure is believed to be small. This is a non-regenerable sulfur removal process, and the cost of ZnO replacement becomes significant for sulfur levels in the fuel greater than 1000-2000 PPM. The average sulfur level of a number 2 fuel oil is about 2400 PPM, with a specification limit of 5000 PPM. For #2 or heavier fuels a regenerable sulfur scrubber could be economically beneficial. For the present ZnO scrubber, the effects of pressure, sulfur concentration, time and temperature still require technological verification.

3.3.2 Reformer Description

The reformer catalytically converts desulfurized fuel and steam into a hydrogen rich process gas. Structurally the reformer is a number of tubes suspended in an internally insulated pressure vessel. Figure 3-4 shows a cut-away view of one of these tubes. At the bottom of the tube, fuel and steam enter the annular gap containing reform catalyst. The heat necessary for the reaction is supplied from burner gas passing counterflow to the fuel/steam mixture through an outside adjoining annulus. In addition, heat is recovered from the hot product gas flowing through the innermost regenerator gap. The reformer burner is located above the tubes and consequently the tube materials must be protected from high flame temperatures. Packing is used in the burner gas stream to improve the heat transfer in the colder tube areas.

Figure 3-4. Reformer Tube Configuration

3.3.3 Impact of Pressure on Reformer

The following equations describe the basic reactions taking place in the steam reforming of a naphtha fuel.

1. Reforming: $\text{CH}_2 + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + 3\text{H}_2$
2. Shifting: $\text{H}_2 + \text{CO}_2 \rightleftharpoons \text{H}_2\text{O} + \text{CO}$
3. Methanation: $\text{CO} + 3\text{H}_2 \rightleftharpoons \text{CH}_4 + \text{H}_2\text{O}$

In the product gas H_2 and CO represent gases potentially usable by the fuel cell while CH_4 is an inert in the power section. The final gas composition leaving the reactor is a function of temperature and pressure. Higher pressures tend to promote the methanation reaction in the reformer, reducing available H_2 and increasing the CH_4 content of the product gas. This effect can be countered by increasing the

temperature of the reform reaction. Figure 3-5 shows the relationship between system pressure and reform equilibrium temperature which assures high fuel conversion.

Figure 3-5. Influence of Pressure on Reformer Parameters

Higher operating pressures also require more energy to drive the system air compressors. This energy is supplied by decreasing the amount of hydrogen consumed in the fuel cell. The excess H_2 from the anode goes to the reformer burner where it raises the temperature of the reformer burner exhaust. The hot gas is then expanded through the power recovery turbine. Reducing H_2 consumption in the stack is equivalent to lowering the reformer efficiency. Figure 3-6 shows this relationship between reformer and fuel cell efficiencies as a function of pressure.

As mentioned above two consequences of operating at higher pressure result in elevated temperatures for both the reformer product and burner exhaust gases. This effect places additional stresses on the materials of construction, which can be alleviated by altering the reformer tube configuration.

Figure 3-6. Relationship Between Fuel Cell and Reformer Efficiencies

The benefits of higher pressure in the reformer include higher catalyst activity and improved heat transfer. Both factors tend to reduce tube lengths and consequently tube costs. Figure 3-7 shows how the reformer tube length varies with system pressure. As shown in the same figure, another method of reducing the required tube length is to increase the heat transfer from the burner gas to the reform gases. This approach in conjunction with increased pressure can appreciably reduce the cost of the reformer tubes.

While the tube costs are reduced, Figure 3-8 shows that reformer costs rise at higher pressures. This is primarily due to the need for a thicker containment vessel which more than compensates for the savings resulting from shorter reformer tubes. Improving the burner heat transfer shows an additional cost benefit relative to the 50 psia, present reformer configuration, up to a system pressure of 170 psia. Above this pressure, vessel costs dominate reformer costs making it more expensive than the baseline design reformer.

Figure 3-7. Influence of Pressure on Reformer Tube Length

Figure 3-8. Influence of Pressure on Reformer Parameters

3.3.4 Areas for Reformer Technology Improvements

To achieve significantly higher pressures in the reformer will necessitate changes in the reactor tube to limit maximum wall temperatures while still maintaining high fuel conversion. This can be achieved either by changes in the tube configuration for more optimum heat transfer or alternately by the use of improved high temperature materials.

Another problem associated with higher pressures and temperatures, especially at the reformer inlet, is the potential for carbon formation on the catalyst due to fuel cracking. More active reform catalysts resistant to carbon laydown over extended periods of time may be required for operation at significantly higher pressures.

In addition to higher pressures which normally improve heat transfer, additional heat transfer enhancement in the burner gas stream by use of mechanical devices can significantly reduce reformer size.

3.3.5 Impact of Pressure on the Shift Converter

The function of the shift converter is to convert carbon monoxide to hydrogen. The reaction is:

In the reference multi-megawatt fuel cell system, this shift reaction is accomplished in two steps, high temperature, (>600°F) and low temperature (350-600°F). The high temperature shift converter accomplish 60% of the conversion and uses a relatively inexpensive catalyst that has low activity below 600°F. The low temperature shift catalyst has good activity below 600°F but it is more costly. The apportionment of the shift reaction to two components optimizes the total cost and degree of carbon monoxide conversion.

Pressure has no thermodynamic effect on the equimolar shift reaction. However, reaction rates tend to increase due to the availability of more internal catalyst surface area at elevated pressures. Higher pressure lowers the amount of catalyst required for both high and low temperature catalysts as shown in Figure 3-9.

Figure 3-9. Effect of Pressure on Shift Converters

While catalyst costs drop with increasing pressure, the surrounding pressure vessel becomes thicker and more costly. Overall shift converter costs decrease only slightly at higher pressures as shown in Figure 3-10.

Figure 3-10. Influence of Pressure on Shift Converter Costs

3.3.6 Impact of Pressure on the Turbocompressor

The turbocompressor pressurizes air for both the fuel cell power section and the reformer burner. The air compressor portion of this unit is driven by expanding the reformer burner exhaust through the turbine. Achieving good efficiencies for this component becomes increasingly difficult at the higher pressure ratios required for system operation above 50 psia.

It is important to maintain high turbocompressor performance. If the turbocompressor efficiency drops, more fuel must be burned to drive the turbine and subsequently less fuel is available to the fuel cell power section. This requires the fuel cell stacks to operate at higher efficiency and lower power density in an effort to maintain a constant overall power plant efficiency. Therefore, as shown in Figure 3-11, fuel cell stack costs are strong functions of turbocompressor performance.

The present multi-megawatt system design uses a single stage radial flow compressor to achieve a 50 psia operating pressure. At higher pressures a multi-stage radial flow compressor is optimum to minimize cost and meet efficiency requirements. The turbocompressor is designed for good efficiency at rated power gas flows.

Figure 3-11. Effect of Turbocompressor Efficiency on Fuel Stack Cost

At low power plant power output, the air flow and outlet pressure from the turbo-compressor must be kept constant to insure proper transient response. At low power, an auxiliary burner maintains the turbine inlet temperature at a sufficient level to provide constant air flow. The use of this burner tends to lower system efficiency, especially as load is backed off from the rated design point. At about 30% of rated power, a second and smaller turbocompressor optimized for the lower air flow is brought on-line, which increases system efficiency at low power levels as shown in Figure 3-12.

Figure 3-12. Power Plant Part Power Characteristics

3.3.7 Areas for Turbocompressor Technology Improvements

Turbocompressor technology improvements are warranted to lower costs, increase efficiency, and enhance reliability. Effort could be applied to the present radial-flow dual turbocompressor and to a number of options including axial flow and variable geometry turbocompressors, and positive displacement machines.

Axial flow turbocompressors are generally more efficient than the radial designs for a fixed size and pressure ratio. However, radial turbocompressor designs are less costly in the size range of interest for dispersed power plants. Further development of axial machines to lower their costs are needed to make them competitive for this specific application.

The present flow radial turbocompressor is a fixed geometry configuration and high and low-flow units are required to meet fuel cell efficiency requirements at low loads. A variable geometry turbocompressor, containing two or more variable components to alter its aerodynamic performance, might be able to eliminate this need

for two units, maintaining adequate efficiencies over the entire range of fuel cell output.

Other options which should be evaluated for this application but which have only briefly been studied include the use of positive displacements machines.

3.3.8 Impact of Pressure on Fuel Cell Stacks

The fuel cell electrochemically combines H_2 from a reformed fuel and O_2 from air to generate D.C. power. The amount of energy supplied is a function of the quantity of H_2 reacted and the cell voltage. Not all of the H_2 in the reform gas can be consumed in the cell stacks.

Cell voltage and current density are the other factors which determine stack efficiency and power output. The cell performance is determined thermodynamically by the fuel and oxidant gas compositions, system pressure, and temperature. Performance is also a function of the kinetics such as the rate of diffusion of H_2 and O_2 to the catalyst surfaces and into the electrolyte. Faster gas kinetics result in lower cell losses (polarizations) and therefore higher cell voltages.

Higher pressures result in an increase of the stack volts per cell at a given current density, as it both raises the thermodynamic theoretical potential and lowers cell polarization losses.

Higher temperatures actually decrease the theoretical cell voltage. However, improved catalyst activity results in a net performance gain.

Cell temperature and pressure are related by two requirements. The cell waste heat must be hot enough to raise steam at a pressure sufficient for use in the reformer. In addition, the temperature for any given pressure cannot be raised too high or electrolyte losses can become significant.

Figure 3-13 shows cell voltage as a function of current density at three pressures, 50, 120 and 200 psia. Each pressure has an associated cell temperature, approximately 400°F for 120 and 200 psia, and 375°F at 50 psia. As shown, higher pressures and the associated increased temperatures substantially improve cell performance.

Figure 3-13. Fuel Cell Performance vs. Pressure

A potential disadvantage of higher temperatures and pressures is that both tend to accelerate the corrosion of cell materials. While these corrosion mechanisms are not well understood, experimental and analytical data indicates that present materials will be satisfactory for 40,000 hours at 120 psi and 400°F.

Higher fuel cell performance imposes additional design requirements such as those discussed in Section 2.6.2 of this report. High performance reduces the cell stack size. More cell coolers and sufficient electrolyte for the goal cell life must be stored into a smaller package. All these variables are accounted for in Figure 3-14 which shows the relative fuel cell cost as a function of pressure. Raising cell pressure from 50 to 200 psia lowers cell costs a very significant 40%.

Figure 3-14. Fuel Cell Cost vs. Pressure

In summary, higher pressure benefits cell performance and cost. The primary technological concern associated with higher pressure is cell life. This is affected by electrolyte loss and corrosion. Other life limiting factors include platinum dissolution and recrystallization. The effects of temperature and pressure on these factors are not completely understood and require further study.

3.3.9 Major Conclusions of Higher Pressure Systems Study

For multi-megawatt fuel cell power plants, cost drops as pressure is increased. Raising the operating pressure of a 4.5 MW system from 50 psia to 200 psia reduces its relative cost 11%. Most of this benefit is due to savings made in the fuel cell stacks and system heat exchangers. Figure 3-15 shows both the total installed power plant cost and the fuel cell stack costs as a function of pressure. These costs assume a 4.5 MW power plant at constant efficiency in large-scale production. As shown, the major cost savings are achieved going from 50 to 120 psia. From 120 to 200 psia, or higher, there is little additional cost benefit.

Figure 3-15. Results of Cost Study as a Function of Pressure

Before the savings associated with higher pressures can be realized, a number of areas require either technological verification or improvement. These improvements include the following:

- A) Reformer tube configuration changes to limit metal wall temperatures to allowable levels while maintaining high fuel conversion
- B) Improvement in catalyst properties, primarily at the reformer inlet, to reduce any tendency for carbon to form at elevated temperatures and pressures
- C) Development of higher temperature materials for reformer hot sections and external heat exchangers to ensure a higher level of structural integrity
- D) Identification of high pressure ratio (10-13) turbocompressor which achieves high efficiency (>70%) and low cost

- E) Improved understanding of factors affecting fuel cell life at elevated pressures and temperatures

3.4 PROCESSING CONCEPTS FOR HANDLING HEAVIER FUELS

3.4.1 Desirability of Utilizing Heavy Fuels

Present commercial fuel cell power plants are designed using a conventional steam reformer to convert hydrocarbon fuels to a hydrogen rich process gas to be used in the fuel cell power section. The steam reformer is limited in the quality of fuel it can process with existing technology. These fuels are generally the lighter hydrocarbons such as methane (natural gas), propane and light distillates as well as alcohols. Heavier fuels contain unsaturated hydrocarbons which tend to thermally decompose in the reformer to form solid carbon and tars which degrade the reformer performance. In addition, they contain higher sulfur levels which cannot economically be removed in a preprocessing section.

It is considered desirable to be able to process heavier fuels such as No. 2 oil, which is presently widely used by industry and utilities as well as coal derived distillates which may be available in the future.

To this objective various concepts are presently under development. These are described in the following sections along with an evaluation of the benefits of improvements or alterations to the basic concept or configuration.

3.4.2 General Description of Heavy Fuel System Options

Figure 3-16 summarizes the operation and characteristics of three fuel processing options for handling heavy fuels. The first system utilizes an autothermal reformer (ATR) containing a suitable catalyst. Fuel and preheated steam and air are fed into the reformer. The air reacts with a portion of the fuel in an exothermic reaction raising the temperature of the gases. The remaining fuel then reacts with the process steam in an endothermic reform reaction to produce gases containing, in

part, hydrogen and carbon monoxide. The product gas must then be shifted ($\text{CO} \rightarrow \text{H}_2$) and hydrogen sulfide and ammonia must be removed (not shown in figure) before the gases are fed to the cells. This process is the most developed and results in the simplest reactor design. The gas fed to the cells, however, contains substantial amounts of nitrogen - which tends to reduce the concentration of hydrogen and lowers cell performance.

Figure 3-16. Baseline System Comparison

The second concept, designated as the "hybrid" approach, uses a thermal steam reformer (TSR) in conjunction with an ATR. The TSR is a catalytic reactor in which only steam and fuel are combined to produce a hydrogen rich gas. Heat is added to the reactant gases from an external burner and must be transferred through metal tube walls. For the TSR to achieve high conversion of a heavy process fuel a very high gas temperatures is required, which in turn, necessitates costly materials of construction for the reactor. To reduce this requirement, in the "hybrid" system the TSR is operated at lower temperature with the resultant lower fuel conversion, and the final conversion is accomplished in an ATR. An advantage of this system is

the potential use of relatively heavy fuels such as crude or residual oil. The product gas must be shifted and both hydrogen sulfide and ammonia removed. A disadvantage to this approach involves the use of two reactors in series (TSR and ATR) along with dilute process gases fed to the fuel cells.

The final baseline system for handling heavy fuels uses two catalytic steam reformers operated in a cyclic fashion. While one reactor is being heated by burning the residual gases from the anode, the other reactor is using this stored heat in converting fuel and steam to a hydrogen rich gas for the fuel cells. Although this gas must be shifted and sulfur removed, no ammonia removal is required since air (N_2) is not used in making the product gas. In addition, the gas to the fuel cell is relatively high in hydrogen concentration, again because there is no air used in the gasification process. A disadvantage to this system is the necessity of rapid thermal cycling (minutes) of the reactors and the associated complexity of the valving requirements. This approach also is the least developed of the three approaches discussed.

3.4.3 Overall Power Plant Economic Comparison of Heavy Fuel Systems

A summary comparison is shown in Figure 3-17 of the estimated capital cost of three baseline power plants, each using one of the heavy fuel concepts described above. These are compared to the reference multi-megawatt power plant (FCG-1) operating on light distillate as described in Section 3.2 of this report. The results indicate that at a constant heat rate of 9300 BTU/KW-HR, the ATR system has the highest capital cost while the cyclic system has the potential of a cost approximately equal to that of the FCG-1.

The costs of the three concepts are detailed in Figure 3-18. The major cost elements of the ATR system include the cell stacks and high temperature heat exchangers. The stack costs are high due to the poor quality of the anode gas feed. The heat exchangers are expensive because they must transfer large amounts of heat at high temperature for air and steam preheating. The hybrid and cyclic systems have complex fuel processor reactors and these tend to be, on a relative basis, the higher cost items for these options.

Figure 3-17. Baseline Systems Economic Comparison

Figure 3-18. Major Subsystems Economic Comparison

3.4.4 Autothermal Reformer Operating Conditions and Limitations

High autothermal reactor exit gas temperature favors good fuel conversion, reduces the chance of carbon formation and results in a smaller reactor (less catalyst required). High reactor exit temperatures may be achieved by either adding more air (O_2) to the reactor and thus combusting a larger fraction of the process fuel or by higher preheat temperatures for the process steam and air.

Adding more air to the reactor results in a lower yield of hydrogen in the exit gas. Thus, to maintain a constant power plant efficiency, the cell hydrogen utilization must increase resulting in reduced cell performance.

Increasing preheat temperature is limited by the cost of high temperature heat exchanger materials.

Two operating points were studied - the baseline, which had a 1700°F reactor exit temperature, and a 1700°F preheat temperature. To achieve this condition required an oxygen to carbon ratio of 0.36. The preheat temperature of 1700°F was considered an upper limit in terms of practical heat exchanger materials. The second operating point studied assumed a reactor exit temperature of 1500°F with a preheat of 1700°F. At these conditions the oxygen to carbon ratio could be reduced to 0.30 and hydrogen utilization in the cell could be reduced about 5% over that of the reference case.

Overall power plant studies indicated that the reference system cost was about 95% of that using the lower reactor exit temperature. This was primarily due to the poorer catalyst activity at lower temperature (1500°F), necessitating a larger reactor to achieve required gas conversion.

3.4.5 Impact of Technology Improvements on ATR System

A study was conducted on the ATR system to evaluate both the effects of improving the catalyst activity and reducing the cost of the high temperature heat exchangers. Figure 3-19 shows the results of this study. Assuming a 5 fold increase in

catalyst activity results in a 3.3% reduction in total power plant cost. An activity increase of this amount has been measured on advanced catalysts. Postulating a reduction in heat exchanger costs by a factor of 2 (use of advanced designs with enhanced heat transfer) along with the catalyst improvement would result in a total cost reduction of 12%.

Figure 3-19. Impact of Technology Improvements on ATR System

3.4.6 Alternate ATR System Utilizing a Hydrogen Separator at Anode Inlet

Because the gases entering the fuel cell from an ATR reactor contain large amounts of diluent nitrogen, a study was conducted to evaluate the benefits of placing a hydrogen separator in this inlet gas stream. The proposed system configuration is as shown in Figure 3-20. The hydrogen separator is considered as a generic device and thus was studied over a wide range of operating pressures. Consideration was given to membrane type separators in which the hydrogen product would evolve at low pressure and would require pumping to fuel cell conditions. At the other extreme molecular sieves were considered in which the hydrogen is delivered at high pressure, but the off-gases must be pumped for use in the burner. The study considered

that hydrogen separation would be 100% complete, and the maximum allowable cost for the separation device was determined based on that point where the cost of including the device was just equal to that of the original configuration.

Figure 3-20. ATR with H₂ Separator

The results of this exercise are shown in Figure 3-21 where the allowable cost of the hydrogen separator is plotted against pressure ratio (hydrogen to vent gas pressure). As can be seen, the maximum allowable of \$20/KW occurs at the ideal separator point, that is, where the hydrogen and vent gas pressures are equal, hence there is no penalty associated with parasitic pumping power. For realistic devices such as membranes and sieves, the allowable cost falls off. If more realistic separation factors were included, the allowable costs would be even lower.

Figure 3-21. Allowable Cost of H₂ Separator to Equal Cost of Reference System

3.4.7 Alternate ATR System Utilizing an Oxygen Separator at Cathode Inlet

Consideration was also given to the utilization of an oxygen separator at the inlet of the fuel cell cathode. This would provide a higher oxygen concentration in the cell and result in improved performance. A rough schematic of this approach is shown in Figure 3-22. As shown, the purified air may be used in a single pass through the cells or a recycle may be used to reduce pumping power and separator size.

The results of this study are shown in Figure 3-23 and are presented in a similar fashion to that of the hydrogen separation study. In this evaluation two separation factors were studied, 100% and one yielding a cathode gas containing 50% nitrogen and 50% oxygen. Again the maximum allowable cost for the separation equipment was \$20/KW at the most ideal conditions. Using the more realistic separation factor and operating at some reasonable pressure ratio results in essentially no cost benefit.

Figure 3-22. ATR With O₂ Separator Figure 3-23. Allowable Cost of O₂ Separator to Equal Cost of Reference System

3.4.8 Alternate ATR System Using Cathode Exhaust Directly in ATR Reactor

The reference ATR system, which uses air in the reactor, receives this air directly from the power plant compressor. Steam is provided to the ATR from condensate removed from the cathode exhaust stream and boiled by waste heat generated in the cell stack.

An alternate approach is to feed the cathode vent gases directly to the ATR inlet. The cathode exhaust contains both oxygen (unused in the cell) and product water vapor.

This alternate configuration eliminates the need for water condensation and makes nearly all the fuel cell waste heat available in the form of steam for cogeneration applications. The relative disposition of the fraction of input fuel energy is shown in Figure 3-24.

Figure 3-24 Improved Quality of Waste Heat Using Alternate ATR System

This system configuration, while increasing the high quality waste heat availability by a factor of 8, has a capital cost increase of only 8% greater than a reference ATR system. The cost increase is due primarily to the larger volume of gas being processed in the ATR and to the lower reactant gas concentrations entering the fuel cells which results in lower performance.

3.4.9 Hybrid System Operating Conditions and Limitations

The thermal steam reformer (TSR) in the hybrid system consists of a tubular reactor in which the reform heat of reaction must be transferred from a burner through the tube walls. To achieve high conversion in this reactor requires very high reactant gas temperatures. This is especially true when processing heavy fuels which contain substantial quantities of sulfur. The sulfur tends to reduce the catalyst activity and to compensate for this the reactor must be run at higher temperatures. Hotter operation, however, results in the need for higher quality tubular materials which raises capital cost. In addition, there is a practical upper limit on tube wall temperature to insure structural integrity.

Thus, in the "hybrid" system approach, the TSR is operated at lower temperature so that fuel conversion is between 60 and 65%. This permits the use of relatively conventional materials.

To complete the conversion, the TSR is followed by an autothermal reformer (ATR). The size and thus cost of the ATR is related to the degree of fuel conversion which takes place in the TSR. The less expensive the TSR, the costlier the ATR. Preliminary analysis has indicated that an optimum fuel conversion of 60-65% in the TSR results in the lowest total fuel processor cost.

3.4.10 Impact of Technology Improvements on Hybrid System

A study was conducted to evaluate the reduction in system cost that could be achieved by improvement in the catalyst activity of both the TSR and ATR. A factor

of 5 improvement was assumed for the catalysts, and this resulted in a 7% reduction in total system cost. This made the hybrid system about equal in cost to that of the FCG-1 as seen in Figure 3-25.

Figure 3-25. Applied Technology Areas for Improving Hybrid System

3.4.11 Alternate Hybrid System Using Gas Turbine Bottoming Cycle

An alternate to the hybrid system was evaluated in which the unconverted fuel leaving the TSR was burned and expanded through a gas turbine-generator bottoming cycle. In this approach the ATR reactor is completely eliminated. A simplified schematic of this system is shown in Figure 3-26. The potential advantages of this system, besides the elimination of the ATR, is that the TSR can be run at still lower temperatures and the unconverted fuel can be converted to useful power in the gas turbine.

Figure 3-26. Alternate Hybrid System - Gas Turbine Bottoming Cycle

Results of this study are shown in Figure 3-27, which expresses system cost relative to the baseline hybrid system as a function of the fuel conversion in the TSR reactor. At low conversions, the fuel cell power density is low due to the requirement for high cell voltage to maintain a constant overall system efficiency. When the TSR reactor fuel conversion exceeds 85 to 87%, the alternate system cost is equal to that of the baseline system. In this study the assumption was made that the TSR reactor costs were constant at all conversions and equal to that determined in the baseline system (62%). Thus, for the alternate system described above to be competitive, the ATR catalyst activity must improve sufficiently to allow an 85% fuel conversion in the same size reactor and at the same temperature presently assumed for the baseline.

Figure 3-27. Relative System Cost vs. Fuel Conversion

3.4.12 Areas for Cyclic Reforming Technology Improvements

As mentioned earlier, the cyclic reforming system is the least developed of the three heavy fuel options investigated. It shows significant promise in terms of cost, improved gas conditions to the fuel cells, and simplification of gas scrubbing (no ammonia).

The area which can be identified for further technology improvements is almost entirely related to the catalyst. This would include increased activity in the presence of heavy fuels, long term thermal cycling verification, resistance to the potential for oxidation resulting in catalyst degradation, and resistance of carbon formation caused by aromatics in the fuel. In addition to the above, the valving equipment for the reactors must be developed for long term operation.

3.4.13 Major Conclusions of Heavy Fuel System Studies

Three system options have been identified which have the potential for processing heavy fuels and making them suitable for fuel cell application. The projected cost

of these systems varies from 20% higher than the baseline acid system operating on light distillate naphtha to about 6% below this cost. The technology level of each of these concepts is in its early stages, and it is difficult to make a specific selection based on presently available data.

It appears, however, that the baseline system efficiency of 36.7% can be achieved for each approach. In addition, an area common to all concepts, which will require development, is the fuel conversion catalyst. The requirements will be somewhat different depending on the concept being developed, but in general catalysts will require higher fuel conversion at reasonable temperatures and will have to maintain this level of conversion in the presence of high levels of sulfur and unsaturated hydrocarbons.

In addition, heavier fuels generally contain higher amounts of sulfur. It is therefore necessary from an economic and maintenance standpoint to develop a regenerable desulfurization system. The use of the present zinc oxide absorbent is effective but can add significantly to operating costs when fuels with several thousand parts per million of sulfur are used.