An Analysis of the Application of Fuel Cells in Dual Energy Use Systems

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ABSTRACT

This study was conducted to assess the technical and financial issues associated with utility-owned, grid-connected, dispersed fuel cells operating as dual energy use systems (DEUS) to

- Provide economic intermediate or peaking duty for the electric utility system, and
- Satisfy thermal loads in the residential, commercial, industrial and utility sectors.

The primary objective was to evaluate the potential applications of dual energy use fuel cell systems by

- Identifying representative generic applications for DEUS fuel cells.
- Assessing the technical and economic factors in each application.
- Developing and evaluating options for matching or decoupling electric and thermal loads.
- Quantifying the potential benefits and limitations of DEUS fuel cells.

Both the phosphoric acid and molten carbonate fuel cell types were considered.

The results indicate that both fuel cell types are economically attractive and technically viable for DEUS use in each of the application sectors. The most attractive applications for

building systems include universities and hospitals; for industry, paper and pulp mills; and for utility power plants, air preheating. The economic benefits from these uses would justify increases in fuel cell capital costs of ∿$300/kw. Several other applications also showed favorable results, with increased allowable capital costs of $100-$300/kw.

The results also indicated that the economic benefits arose even if the DEUS power plants operated on economic electric dispatch. This mode also resulted in significant petroleum savings due to the approximately 80% efficiency of DEUS fuel cells.

Very few limitations on the use of DEUS fuel cells were identified. It was noted that the quality of reject heat from the phosphoric acid power plant, while satisfactory for all residential-commercial applications, is not sufficient to meet certain industrial requirements. This did not, however, represent a significant limitation due to the relatively large number of applications where the quality of heat was adequate.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

This project assessed the benefits and limitations of dispersed fuel cell power plants operating as dual energy use systems (DEUS). In concept, DEUS power plants would be installed by the electric utility for economical generation of electric power. The DEUS power plant would be located near the user of thermal energy, which would be supplied by the fuel cell reject heat. This project identified the most promising applications for the DEUS fuel cell: A methodology was developed for determining the allowable increase in capital cost for DEUS fuel cells. Allowable capital cost increases and energy savings were determined for each application.

PROJECT OBJECTIVE

The objective of this project was to determine whether DEUS fuel cell power plants are technically viable and economically attractive options, warranting utility industry consideration. The results should be of interest to environmentally constrained utilities, utilities considering the deployment of small DEUS or cogeneration systems, or utilities seeking the fuel savings offered by the DEUS concept.

PROJECT RESULTS

Several residential, commercial, industrial, and utility applications for DEUS fuel cells were identified. In most cases significant increases in the allowable fuel cell capital cost could be justified by the utilization of the reject heat. Allowable increases ranged from \$100 to \$400 per kilowatt. Overall DEUS fuel cell efficiencies generally exceeded 80%. A surprising result was that phosphoric acid power plants rejecting heat at 160-350°F were nearly as applicable as molten carbonate power plants rejecting heat at 160-1000°F. The study indicated that fuel conservation would be a major benefit of DEUS fuel cells operated by an economical electric dispatch strategy. Although greater economic and total energy savings could accrue to DEUS fuel cells operated by a thermal dispatch strategy, it was shown that such a strategy tended to displace coal and nuclear power with oil and was therefore less attractive.

In summary, this preliminary assessment indicates that utility-owned, grid-connected DEUS fuel cells have great potential and should be investigated in more depth--possibly by considering a few site-specific cases.

Arnold P. Fickett, Project Manager
Fossil Fuel and Advanced Systems Division

Note: A summary of this project is contained in EM-981-SY, Volume 1.

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Section 1

INTRODUCTION

BACKGROUND

Fuel cells, because of their high electrical conversion efficiency, and other unique advantages, offer significant benefits to electric utilities. The first generation (phosphoric acid - "Type I") fuel cell is in the demonstration stage and is expected to be commercially available within several years. Research and development efforts are underway to develop a more efficient second generation (either an advanced phosphoric acid or molten carbonate - "Type II") fuel cell within the next decade. Studies conducted by Public Service Electric and Gas Company (PSE&G)* and Burns and McDonnell** have shown that fuel cells have the potential for significant penetration in both large and small utility markets (1), (2).

Since fuel cells in utility grids can be sited near the loads, they offer an opportunity for the utilization of the thermal energy which would otherwise be rejected. Dual energy use sytems (DEUS), which utilize both electricity and thermal energy from power generation, provide a significant opportunity for conservation of primary energy resources. Various concepts for DEUS are technically feasible, including district heating, total energy and industrial cogeneration with steam or gas turbines (3). DEUS fuel cells offer certain advantages over other approaches for utilization of reject heat.

This report describes the results of a study of utility-owned, grid-connected, dispersed fuel cell power plants with recovery and

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* PSE&G, Economic Assessment of the Utilization of Fuel Cells in Electric Utility Systems, EPRI EM-336, Final Report, Nov. 1976.

**Burns and McDonnell, An Assessment of the Fuel Cell's Role in Small Utilities, EPRI AF-696, Final Report, Feb. 1978.

utilization of reject heat for thermal loads. Various technical, economic and institutional issues associated with such DEUS fuel cell power plants for thermal loads in residential, commercial, industrial and utility sectors have been addressed in this study.

OBJECTIVE

The primary objective of this study was to perform a comprehensive assessment of dual energy use fuel cell systems applications. The assessment included:

- identification of representative generic applications in the residential, commercial, industrial and utility sectors
- assessment of technical and economic factors in each application
- development and evaluation of options for matching/decoupling electric and thermal loads
- evaluation of fuel cells in the DEUS mode versus "conventional" fuel cell systems
- identification of specific changes in the fuel cell configuration to make DEUS applications more attractive
- identification of potential benefits and limitations of DEUS fuel cells versus other methods of reject heat utilization
- definition of improvements in fuel cell technology and/or system development needs to overcome limitations.

OVERVIEW OF THE FUEL CELL

A fuel cell is an electrochemical device which directly converts the chemical energy of a fuel to direct current (dc) electricity without involving combustion or mechanical drive (4). A simplified description of fuel cell operation by Mr. Arnold P. Ficket of the Electric Power Research Institute follows (5)

> The fuel cell converts the chemical energy of a fuel directly to dc power without an intermediate combustion or thermal cycle. A single cell (shown schematically in Figure 1-1) produces 0.5-1.0 vdc at a current that is proportional to the cell area. Individual cells are connected in series, as in a lead acid battery, to result in a stack (power section) with an output voltage compatible with the application. This output can be several hundred volts.

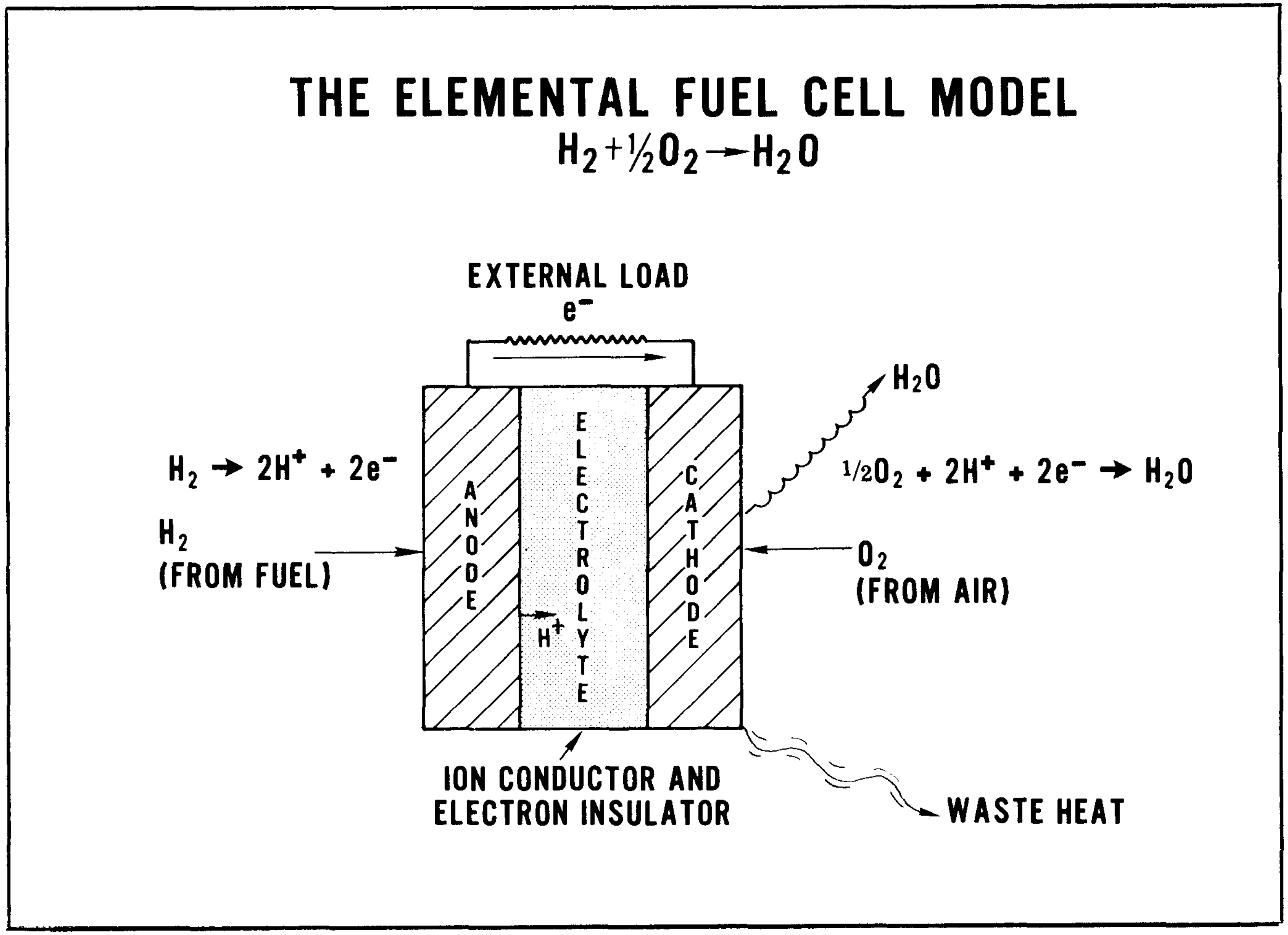

Figure 1-1. Schematic Diagram of a Fuel Cell.

> In order for a fuel cell power plant to be a useful part of an electric utility system, it must be able to use available fuels and produce ac power. Thus a complete fuel cell power plant includes a fuel processor and a power conditioner. The fuel processor converts a utility fuel to a hydrogen-rich gas and the power conditioner converts dc power to ac power compatible with the utility bus.

A fuel cell power plant consists of three major parts -- a fuel processor, fuel cell stacks and a power inverter. The fuel processor accepts a hydrocarbon fuel such as natural gas, distillate fuel oil, naphtha, etc. and converts it to a hydrogen-rich gas which is fed to the cell stacks. The cell stacks produce dc power. This is converted to alternating current (ac) power for utilization in electric utility grids by the inverter. The electrical efficiency of the power plant, using naphtha or distillate oil, is about 38-40% for the first generation systems (6). The second generation fuel cell is expected to have an electrical efficiency of approximately 48-50 percent.

POTENTIAL ROLE OF FUEL CELLS IN LARGE AND SMALL UTILITIES

Electric utilities are experiencing increasing difficulties in adding power generation capacity because of high capital costs, long lead times and environmental problems associated with conventional power generation alternatives. Fuel cells offer a flexible option with a number of inherent advantages:

- greater conversion efficiency than conventional thermal generators
- modularity in design so that small fuel cell generators can operate as efficiently as large ones
- siting flexibility and shorter construction times because of modular design
- relatively flat heat rate vs load, thus offering greater economics at part load performance or for spinning reserve capability
- environmentally more attractive because of low emissions, quiet operation and negligible water requirements.

These advantages make fuel cells attractive for power generation in both large and small electric utilities. The exact role of fuel cells in the future generating mix of a utility would depend on a number of important factors such as the system load duration curve, capital and operating costs of alternative technologies and the existing generation mix.

A typical load duration curve is shown in Figure 1-2. For any utility, the economic problem involves minimizing the total cost of supplying the electricity requirements, represented by the area under the load duration curve, at an adequate reliability level. Base load power generation is generally accomplished with technologies having high fixed costs and low variable costs. Peaking power, on the other hand, is provided by technologies with low fixed costs but high variable costs. Intermediate power resources fall somewhere in between base and peaking resources in both fixed and variable costs. Fuel cells can provide both peaking and intermediate resources for both large and small utilities and may possibly serve as baseload resources for small utilities.

Role of Fuel Cells in Large Utilities

The Public Service Electric and Gas Company (PSE&G) study included an economic assessment of the potential role of fuel cells in typical electric utility systems (1). The objective of this study was to evaluate the long range economic benefits of the first generation (Type I) and advanced (Type II) fuel cells in the generating mix of a representative electric utility system. The benefits of the unique characteristics of the fuel cell were quantified in this study.

The analysis was based on a reference utility whose characteristics were representative of large U.S. electric utilities. Future capacity additions to this reference utility were evaluated on a long range optimum generation mix basis to minimize total present worth of all future revenue requirements to cover capital related charges and production costs. The market penetration of fuel cells for different combinations of operating characteristics, fuel price and capital costs was estimated by providing the fuel cell as an alternative in the optimum expansion plan of the reference system. Sensitivity analyses were performed to characterize the impact of major parameters on fuel cell penetration.

A summary of the results of the PSE&G study is shown in Table 1-1. Fuel cell penetration varied from as low as 4% for Type I fuel cells with start up costs included to almost 80% for Type II fuel cells. It was determined that Type I fuel cell penetration was very sensitive to small changes in the total present worth of capital related and

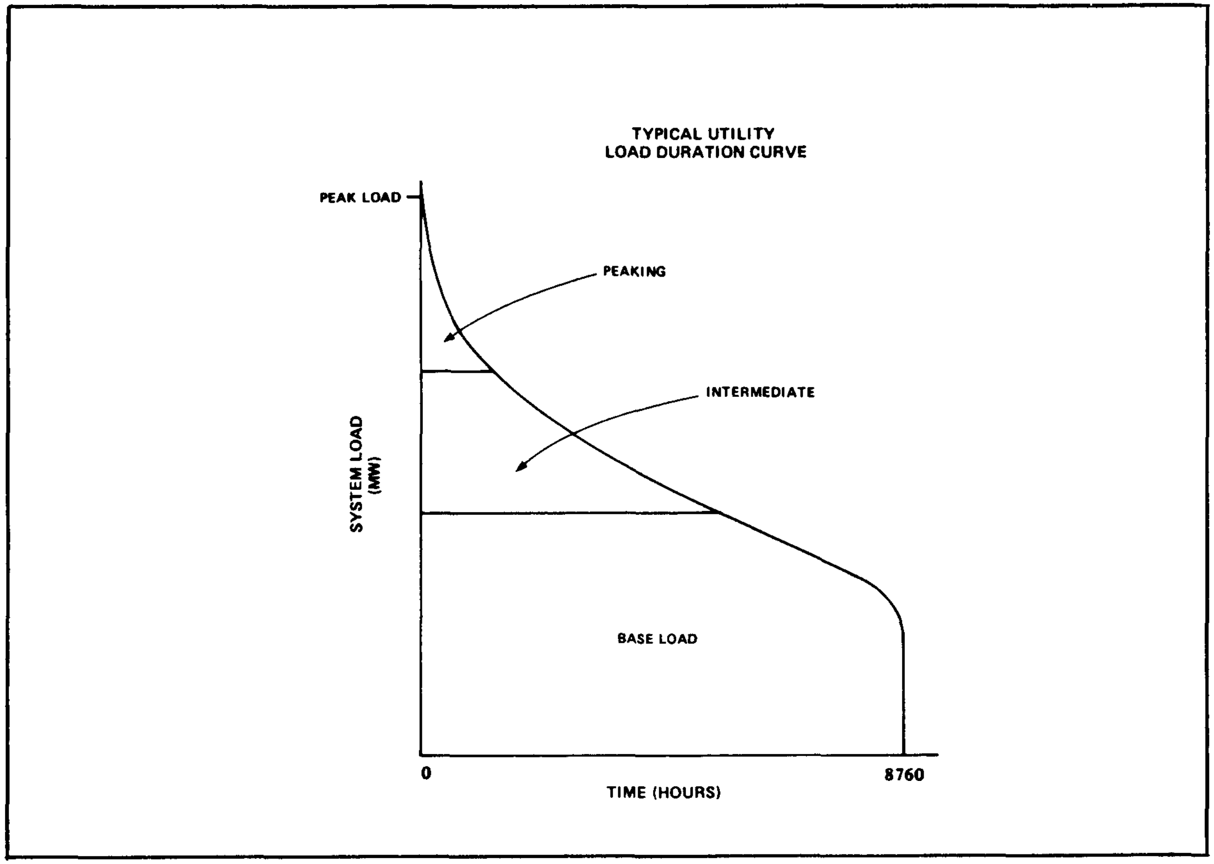

Figure 1-2. Typical Utility Load Duration Curve.

Table 1-1

SUMMARY OF FUEL CELL PENETRATION FOR DIFFERENT SCENARIOS

Fuel Cell					
Heat Rate Btu/kWh	Operating Cost* (mills/ kWh)	Capital Cost $/kW	Fuel Price Scenario	Special Case	Fuel Cell Penetration
9300	22.79	250	Base	Fuel Cell Start-up Costs Included	0-20%
9300	22.32	250	Low	-	
7500	18.38	350	Base	Nuclear Fuel 45c/MBtu	
9300	22.79	250	Base	70% Load Factor	
9300	22.79	250	Base	-	20-40%
7500	29.25	200	High	-	
7500	22.05	200	Base	Nuclear Fuel 45c/MBtu Fuel Cell Fuel at 20% Premium	
7500	18.38	300	Base	Nuclear Fuel 45c/MBtu	40-65%
7500	22.05	200	Base	Fuel Cell Fuel at 20% Premium	
7500	18.38	200	Base	-	75-80%
7500	18.38	200	Base	70% Load Factor	
7500	18.38	200	Low	-	

* Operating cost (mills/kWh)
(fuel only)
$$= \text{heat rate (Btu/kWh)} \times \frac{\text{fuel price (\$/MBtu)}}{1000}$$

Source: Public Service Electric and Gas Company: Reference (1) production costs over the 20 year period, because of the relatively small economic advantage of Type I fuel cells over conventional intermediate resources. Type II fuel cells have a greater economic advantage and consequently less sensitivity.

Breakeven capital costs were calculated for Type I and Type II fuel cells vs two different types of conventional generation. Figure 1-3 summarizes some of the results. With the baseline assumptions, the Type I fuel cell represented 4784 MW of capacity in the year 2000 for the reference utility, accounting for about 27% of the 17,364 MW of capacity additions between 1980 and 2000.

Role of Fuel Cells in Small Utilities

Burns and McDonnell performed an assessment of the role of fuel cells in small utilities (2) with peak demands in the range from 2 to 500 MW. Six reference utility systems and four fuel cell types were examined in the study. An analysis of the percentage penetration of intermediate capacity into the total power resource mix for each reference system was conducted for fuel cells (all types) and conventional systems. The results indicated, in general, that fuel cells would achieve a greater penetration (than conventional generation) into the power resource mix of the six reference systems for optimum expansion types. Table 1-2 shows some of the results.

A sensitivity analysis of fuel price variation and capital costs of base load generating capacity was conducted. The results indicated that these factors did not significantly influence fuel cell market penetration. Breakeven capital costs were calculated with each of the six reference utility systems. In general, these breakeven capital costs were higher than the assumed input capital costs and were in the $250-400/kW range.

The estimated market penetration, calculated for generating systems only, ranged from 21,785 MW to 45,201 MW for the year 2000. The fuel cell characteristics determined to be most significant were size, capital cost, heat rate, and operation and maintenance costs. Other factors which could significantly affect fuel cell market penetration included potential advances in conventional technology which could compete with fuel cells in the small utilities market, and potential restrictions on oil fired generation.

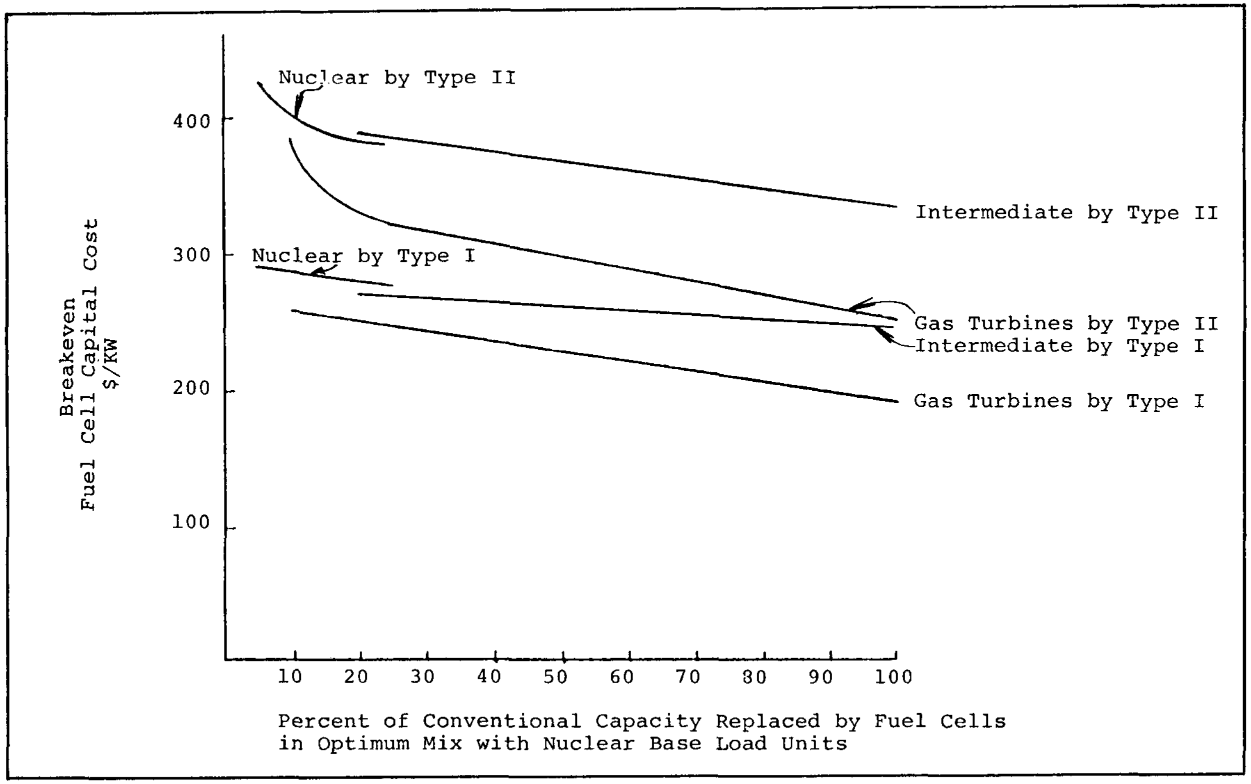

Figure 1-3. Breakeven Fuel Cell Capital Cost for Different Market Penetrations Using Base Fuel Prices.

Source: Public Service Electric and Gas Co., Reference (1)

Table 1-2

COMPARISON OF OPTIMUM FUEL CELL VS CONVENTIONAL EXPANSION PLANS FOR SMALL REFERENCE UTILITIES

REFERENCE SYSTEM	TYPE OF CONVENTIONAL EXPANSION	CONVENTIONAL PENETRATION	FUEL CELL PENETRATION	
			5 MW TYPE I	5 MW TYPE II
35-MW NC Municipal	8 MW Diesel	54	54	59
35-MW NE Municipal	8 MW Diesel	40	40	55
10-MW Municipal With Generation	3 MW High Speed Diesel	27	27	47
10-MW Municipal Without Generation	3 MW High Speed Diesel	40	50	40
35-MW Distribution Cooperative	8 MW Diesel	50	50	57
200-MW GNT Cooperative	150 MW Combined Cycle & 50 MW Combustion Turbine	45	45	51

Source - Burns and McDonnel: Reference (2)

FUEL CELLS FOR DUAL ENERGY USE SYSTEMS

If fuel cells achieve a significant market penetration in large and/or small utilities, it is likely that, because of their modularity and siting flexibility, they would be located in close proximity of the loads. Grid-connected dispersed fuel cell power plants could be equipped for reject heat recovery and distribution to serve as dual energy use systems (DEUS) plants for residential, commercial, industrial and/or utility applications. Figure 1-4 shows a schematic representation of a "conventional" and a DEUS fuel cell. In order to assess the potential viability, benefits and limitations of DEUS fuel cells, it is necessary to address the following types of issues:

- what are the potential applications for thermal energy utilization in the residential, commercial, industrial and utility sectors and what are the characteristics (size, frequency, quality and quantity of thermal energy required, etc.) of these applications?
- is it technically feasible to provide the thermal energy needs of these applications with the Type I - phosphoric acid and Type II - molten carbonate fuel cells? Are the quality and quantity of heat available from DEUS fuel cells adequate for these applications?
- what are some of the problems associated with matching and/or decoupling electric and thermal loads? What are the possible solutions?
- what are the most promising applications for DEUS fuel cells and what incremental value ($/kW) can be assigned to the recovery and utilization of reject heat from the fuel cell?
- what are the possible modifications to the fuel cell configuration which would make it more attractive as a DEUS? What are the costs of these modifications?
- are there any institutional constraints which could pose a significant barrier to use of DEUS fuel cells? How can these be solved?
- what are the major benefits/limitations of DEUS fuel cells? How do DEUS fuel cells compare with alternative technologies for reject heat recovery and utilization?
- what are some of the fuel cell research and development needs from the perspective of their potential use in DEUS plants?

These and other relevant questions have been addressed in this study.

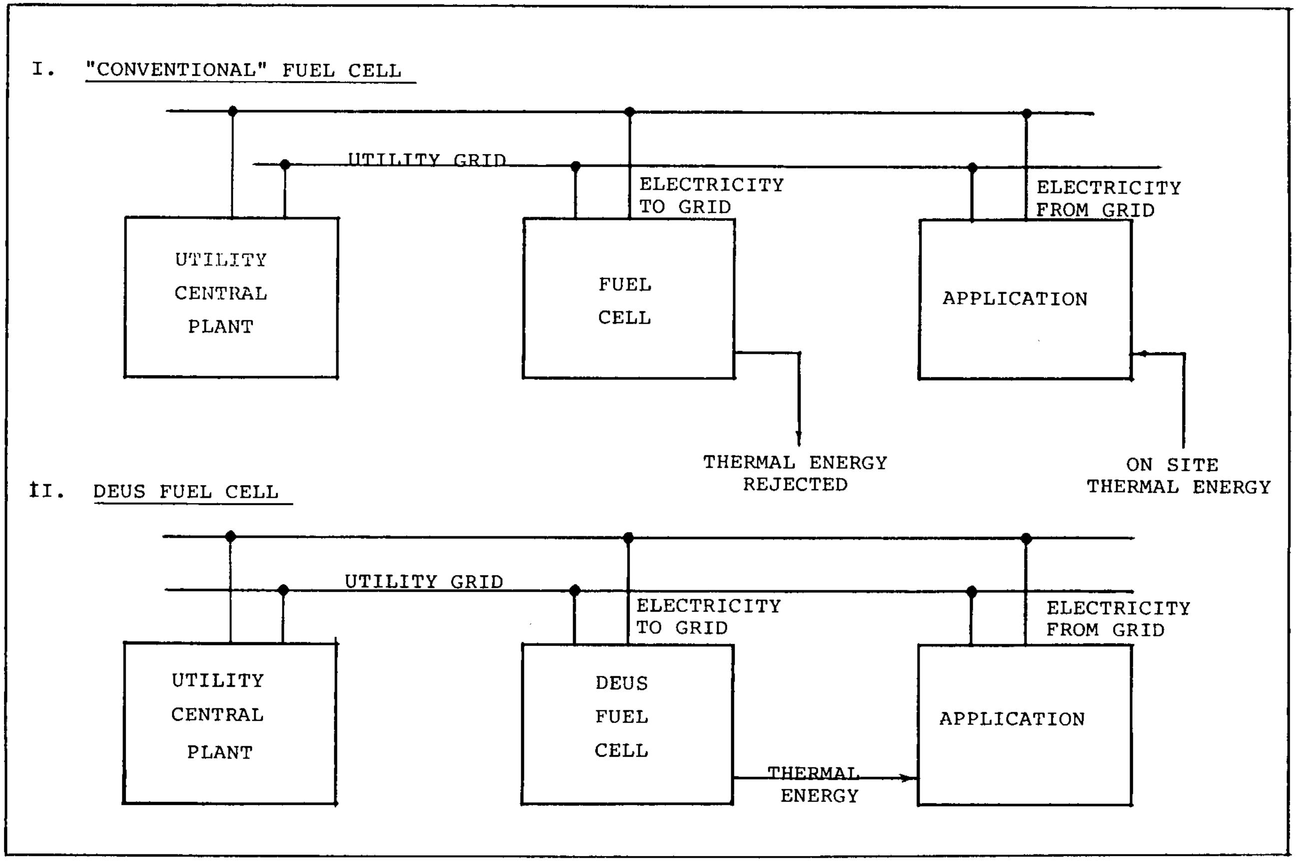

Figure 1-4. Schematic Representation of Fuel Cell in the "Conventional" and DEUS Mode.

SUMMARY OF STUDY APPROACH

A conceptual overview of the approach used in this study is shown in Figure 1-5. The study consisted of four major technical tasks:

Task 1 - Survey of Major Opportunities in Heat Utilization

This task involved a survey of the major heating/cooling applications (residential, commercial, electric utility, and industrial) to determine the generic applications that might provide opportunities for power plant reject heat utilization. For each promising generic application, the quality/quantity as well as load profile of thermal requirements, likely location, and the potential value ($/million Btu) of the thermal energy to the user were characterized. The initial list of opportunities is included in Table 1-3. The existing information sources available to the project team were examined for their relevance to the assessment of DEUS fuel cells. Additional information sources were identified and utilized to develop the necessary information for characterizing the generic applications.

For each generic application, a preliminary analysis of the potential applicability of DEUS fuel cells was conducted. In this analysis, sequential screening criteria were used to identify the most promising applications. The list of applications selected for further analysis is shown in Table 1-4.

Task 2 - Definition of Pertinent Fuel Cell Characteristics

This task included the following activities

- definition of the quality and quantity of reject heat available, along with the heat rate characteristics, at different loads
- comparison of the quality and quantity of thermal energy available with the requirements of the promising generic applications
- identification of possible modifications to the fuel cell configuration or operational characteristics, to better match the availability and requirements of thermal energy
- estimation of the costs of heat recovery and utilization and potential modifications
- development of the characteristics of the modified fuel cell

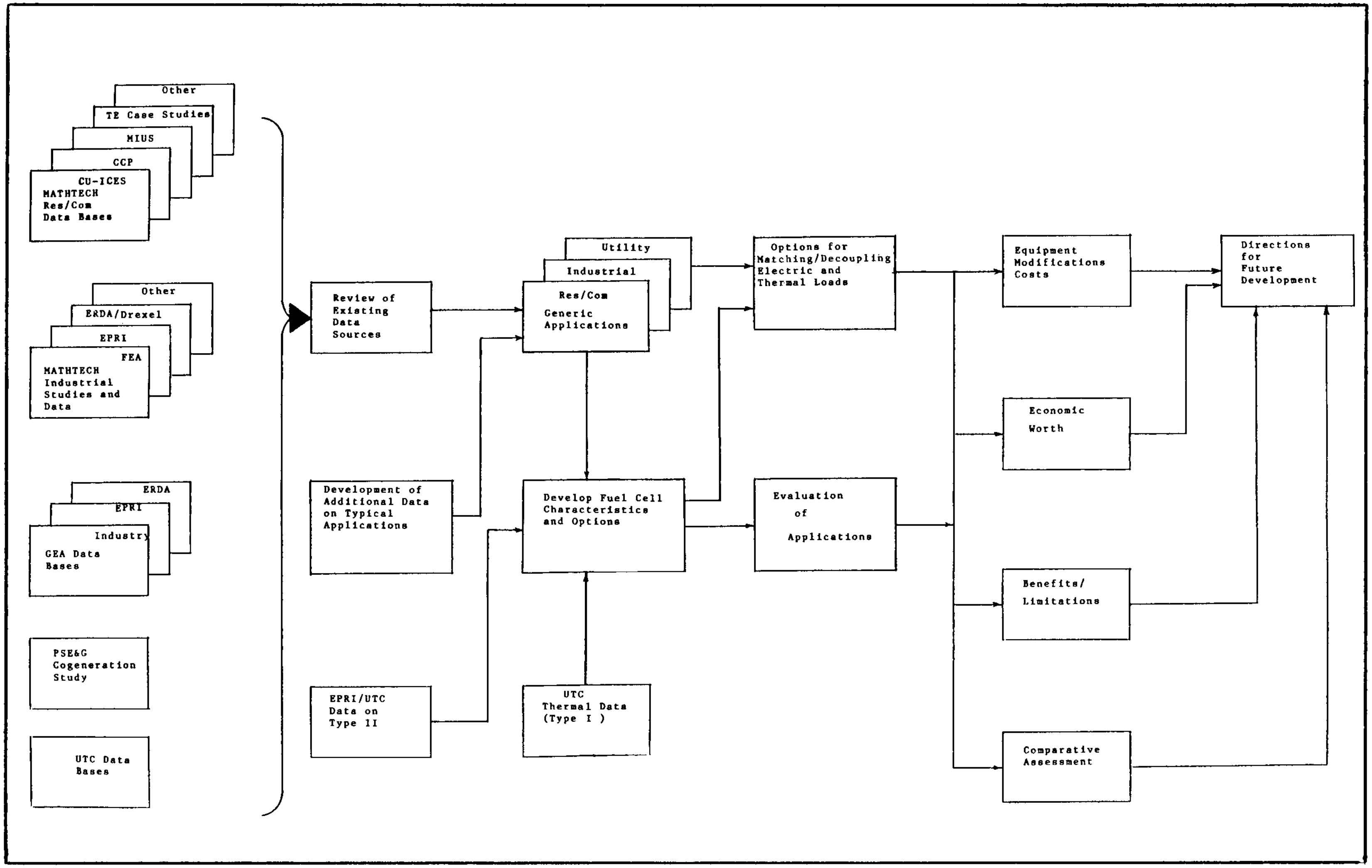

Figure 1-5. Conceptional Overview of Study Approach.

Table 1-3

INITIAL LIST OF GENERIC APPLICATIONS FOR THERMAL ENERGY

BUILDING SYSTEM APPLICATIONS	INDUSTRIAL APPLICATIONS SIC	Industry	UTILITY APPLICATIONS
° Single-Family, Detached Residences	1211	Bituminous Coal	Air Preheat
° Single-Family, Attached Residences	2011,13	Meat and Sausage	Boiler Feedwater and Condensate Heating
° Multi-Family, Low-Rise Apartments	2022	Natural Cheese	Plant Building HVAC and Auxiliary Steam Requirements
° Multi-Family High-Rise Apartments	2023	Cond. and Evap. Milk	Coal Supply Heating
° Mixed Residential Zones	2046	Wet Corn Milling	Combined Cycle Power Plant
° Neighborhood Shopping Center	2062	Cane Sugar Refining	Switching Stations and Substations
° Commercial Strip	2063	Beet Sugar Refining	Fuel Processing Plants
° Regional Shopping Center	2075	Soybean Oil	
° Central Business District	2085	Distilled Liquors	
° Office Buildings/Complex	2261	Cotton Fininshing	
° Hotels/Motels	2262	Synthetic Fininshing	
° Mixed Commercial Zones	2421	Saw and Planning Mills	
° Hospitals/Medical Complexes	2435	Plywood	
° Universities	2436	Veneer	
° Military Bases	2511	Wooden Furniture	
° Primary and Secondary Schools	2611,21 31,61	Pulp and Paper Mills	
° Correctional Institutions	2812	Alkalines	
° Airports	28195	Aluminas	
° Sewage Treatment	2822	Synthetic Rubber	
	2823	Cellulosic Fibers	
	2824	Non-Cellulosic Fibers	
	2865	Crudes and Intermediates	
	2869	Organic Chemicals	
	2911	Petroleum Refining	
	2951	Paving Mixtures	
	3271	Concrete Blocks	
	3321 22,23	Iron and Steel Foundries	

Table 1-4

LIST OF PROMISING APPLICATIONS STUDIED IN TASKS 2 THROUGH 4

BUILDING SYSTEM APPLICATIONS	INDUSTRIAL APPLICATIONS		UTILITY APPLICATIONS
	SIC	Description	
• Mixed Residential	2062	Cane Sugar Refining	° Air Preheat
• Shopping Center	2063	Beet Sugar	° Boiler Feedwater and Condensate Heating
• Central Business District	2865	Cyclic Crudes and Intermediates	° Plant Building HVAC and Auxiliary Steam Requirements
• Mixed Residential/ Commercial	2261	Finishing Plants, Cotton	
• Office Building	2911	Petroleum Refining	
• Hospital	2262	Finishing Plants, Synthetic	
• University	2824	Non-Cellulosic Fibers	
• Military Base	2085	Distilled Liquors	
	2951	Paving Mixtures	
	2812	Alkalies and Chlorine	
	2611,21, 31,61	Pulp and Paper Mills, etc.	

Task 3 - Evaluation of Options for Matching/Decoupling Electric and Thermal Loads

Various options for matching or decoupling electric and thermal loads were identified. These included use of supplementary boiler, thermal storage, interchange of electric power with the grid and purchase or sale of thermal energy. The feasible options for each generic application were then identified and for each option/application combination, an analysis was performed to identify the quality and quantity of thermal energy supplied, revenue from thermal energy supplied, associated electrical production, operating and maintenance costs, fuel costs and capital costs. The breakeven capital costs associated with the recovery and utilization of reject heat were calculated for each application for each relevant matching/decoupling option. In performing these analyses it was assumed that all fuel cell capacity was composed of integral multiples of 4.5 MW. This assumption was based on

- the ready availability of data for a 4.5 MW fuel cell power plant
- an expectation that the first commercially available fuel cells will come in a limited number of sizes and that thermal matching will be required for reject heat utilization

The technical opportunities, barrier and/or constraints to the matching or decoupling of thermal and electric loads with DEUS fuel cells were identified and examined.

Task 4 - Assessment of Potential Benefits and Limitations of DEUS Fuel Cells

This task involved five parts:

- identification of power plant equipment configurations and costs for promising generic applications
- examination of the economic worth of utility-owned, grid-connected DEUS fuel cells
- identification of potential benefits of fuel cells in the DEUS mode
- identification of potential limitations of fuel cells in the DEUS mode
- a qualitative comparative assessment of DEUS fuel cells with alternative means of power plant reject heat utilization such as extraction and back pressure turbines, combustion turbines with heat recovery boiler, diesel engines with heat recovery, etc.

A GUIDE TO THIS REPORT

Section 2 of this report presents information on the basic characteristics of Type I - phosphoric acid and Type II - molten carbonate fuel cells. For Type I fuel cells, possible modifications to improve the heat recovery characteristics were identified and evaluated. Section 3 provides an overview of the analytical methodology used in the study and the assumptions made.

Sections 4 through 6 describe the results of the evaluation of the promising generic applications, including an analysis of the options for matching and/or decoupling electric and thermal loads, economic analysis, and calculation of the breakeven capital cost associated with heat recovery and utilization.

Section 7 summarizes possible implications of DEUS fuel cells in electric utility systems. A qualitative comparison of fuel cells against other methods of reject heat utilization is presented, and the potential benefits and limitations of DEUS fuel cells from an electric utility perspective are identified.

Section 8 summarizes the major findings and conclusions of the study.

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SECTION 2

DUAL ENERGY USE FUEL CELL SYSTEM CHARACTERICTICS

INTRODUCTION

Two different types of fuel cells were considered in this study for DEUS plants:

- Type I - phosphoric acid electrolyte cells
- Type II - molten carbonate cells

The Type I fuel cell is currently entering the demonstration phase, while the Type II fuel cell is still in the early stages of the development of the basic power plant building block. Therefore, considerable more detailed information was available on the Type I fuel cell.

The information required for the evaluation of DEUS fuel cells was the potential availability of thermal energy, by quality and quantity, and the cost of recovery and utilization. Also, possible configuration modifications to increase the quality and/or quantity of thermal energy available were identified. The analysis of potential modifications and the development of information on thermal energy availability for Type I fuel cells was the responsibility of United Technologies Corporation in its capacity as a subcontractor on this project. Information on the Type II - molten carbonate fuell cell thermal energy availability was provided by EPRI based on previous and on-going research efforts.

GROUNDRULES

The following groundrules were adopted in the development of the characteristics of the thermal energy availability for DEUS fuel cells:

- Baseline Design - Most characteristics of the Type I fuel cell are based on a power plant design which utilizes the 4.5 MW Demonstrator concept with some advances in technology. The 4.5 MW Demonstrator (1) is a 4.5-megawatt fuel cell ac electric power generator designed and constructed by the Power Systems Division of United Technologies under a jointly soonsored program with the U.S. Department of Energy, (DOE) and the Electric Power Research Institute (EPRI). The Demonstrator is to be installed and operated by Consolidated Edison Company of New York. The objective of this program is to demonstrate the installation and operation of a multimegawatt generator by a utility company. The primary change from the 4.5 MW Demonstrator due to the technology incorporated for this study is a slightly higher temperature of the recoverable thermal energy.

- Heat Rejection Interface - It was assumed that thermal energy can be recoverd only from the power plant heat rejection interfaces so that the basic electric power generation cycle is not altered. This allows the incorporation of heat recovery capability to be accomplished with minimum modifications to the basic electric generator, and does not require a complete power plant redesign effort.

- Cost Assumptions - All costs have been expressed in 1975 dollars. The capital costs of heat recovery equipment and costs of configuration modifications are expressed as differentials from the baseline fuel cell power plants. Except where the cost impact of system modifications are insignificant, estimated cost differentials are based on yearly power plant production rates of 100 MW and 1750 MW.

- Number of Different Configurations - It is important to note that it would be impractical for a manufacturer of this type of energy-generating equipment to offer catalog models precisely suited for all DEUS applications. For study purposes, however, it was considered reasonable to examine an unlimited number of power plant configurations to identify applications with the potential for installations of significant total megawatt capacity. Some of these applications could require additional consideration for a special power plant configuration.

- Startup - Shutdown and Maintenance - The startup, shutdown and maintenance characteristics are based on the 4.5 MW Demonstrator.

HEAT RECOVERY CAPABILITY OF BASELINE TYPE I POWER PLANTS

The baseline fuel cell power plant of Type I fuel cells corresponds to the fuel cells currently being developed by United Technologies Corporation for commercial application. Figure 2-1 shows the available reject heat as a function of the electrical power output. The data in Figure 2-1 are normalized and expressed on a percentage basis. The heat rate (Btu/kwh) at different electric output levels is shown in Figure 2-2.

Estimated Type I fuel cell electrical and thermal characteristics presented in this report represent an average over the powerplant life. and therefore slightly more available thermal energy. For this report the average electrical efficiency was used and is about 38% based on the higher heating value of the fuel. This average efficiency is also equivalent to a heat rate of about 9000 Btu/Kw-hr, also based on higher heating value. With the installation of heat recovery equipment, reject heat equivalent to about 46% of the input fuel energy (HHV) can be recovered and utilized. This leads to an overall fuel utilization efficiency of about 84% at rated electric output, if all the recovered thermal energy is utilized. Figure 2-1 shows the variation of fuel utilization over the range of electric output.

The thermal energy available can be at two different quality levels. About 20% of the thermal energy can be used to generate steam at 120 psig, 350°F. The remaining 80% is available as 160°F hot water.

At 100% electric output, the breakdown of the input fuel energy per kWh is as follows:

	Btu/kwh
• Electric generated	3413
• Steam at 350°F	870
• Hot water at 160°F	3250
• Unusable reject heat	1467
• Heat rate	9000

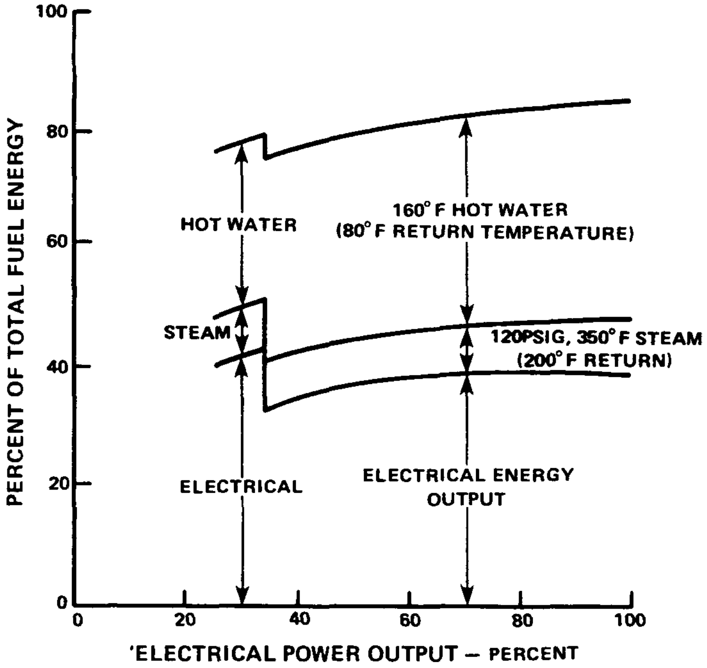

Figure 2-1. Estimated Heat Recovery Capability: Type I - Phosphoric Acid Fuel Cell Power Plant.

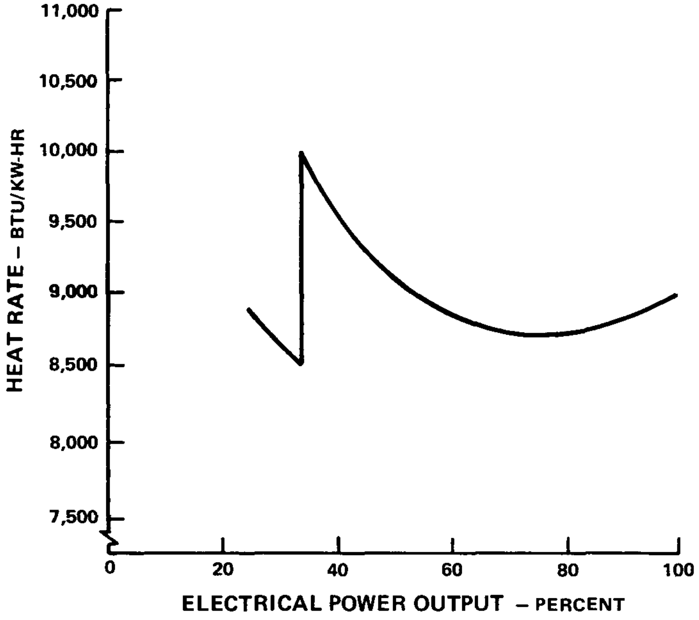

Figure 2-2. Heat Rate vs. Electrical Output: Type I Phosphoric Acid Fuel Cell Power Plant.

TYPE I POWER PLANT MODIFICATIONS FOR HEAT RECOVERY

Thermal Management Subsystem

As indicated earlier, heat recovery was assumed to be accomplished only at the heat rejection interface without altering the power plant electrical system in any way. Therefore, the heat recovery must be accomplished through the powerplant heat rejection components. The configuration of the baseline fuel cell dc module is shown in Figure 2-3. Figure 2-4 shows the thermal management configuration. Power plant waste heat is removed form the dc module via the water recovery condensers, the process air cooler and the stack thermal control heat exchanger and then rejected to the environment by the dry cooling tower (DCT). Cooling tower coolant is circulated through these module heat rejection heat exchangers and heated to 210°F before flowing to the DCT.

Alternative Configurations for Heat Recovery

The baseline power plant can be modified in a number of different ways to recover waste heat. Three different configurations were examined:

- Configuration A - Minimum Modifications
  In this configuration all available thermal energy is hot water at 210°F.
- Configuration B - Modification for Hot Water and Steam Availability
  In this configuration, some energy is available as steam at 350°F and the rest as hot water at 160°F.
- Configuration C - Modification for Additional Steam Availability
  In this configuration, the power plant is capable of generating additional thermal energy (in addition to reject heat from power generation) by burning extra fuel.

Each configuration requires different modifications to the baseline electric generator with the degree of modification increasing with successive configurations. All modifications, however, involve only the power plant heat rejection components - heat exchangers within the dc module and the dry cooling tower.

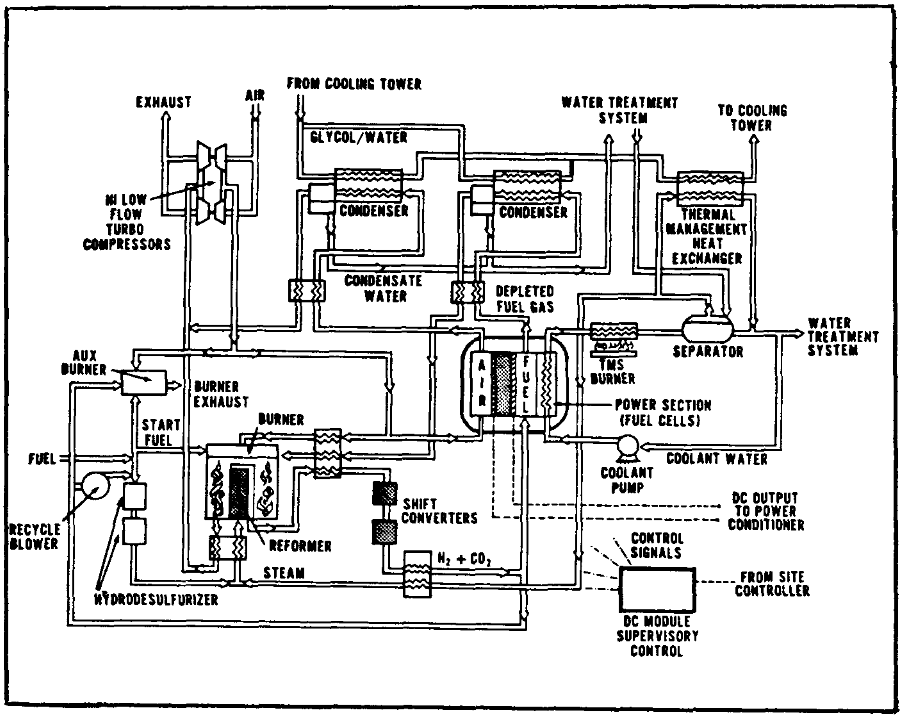

Figure 2-3. System Schematic of the DC Module in the FCG-1 Fuel Cell.

Source: L. M. Handley, et al, "4.8 MW Fuel Cell Module Demonstrator, <u>Proceedings of the New Intersociety Energy Conversion Engineering Conference</u>, 1977.

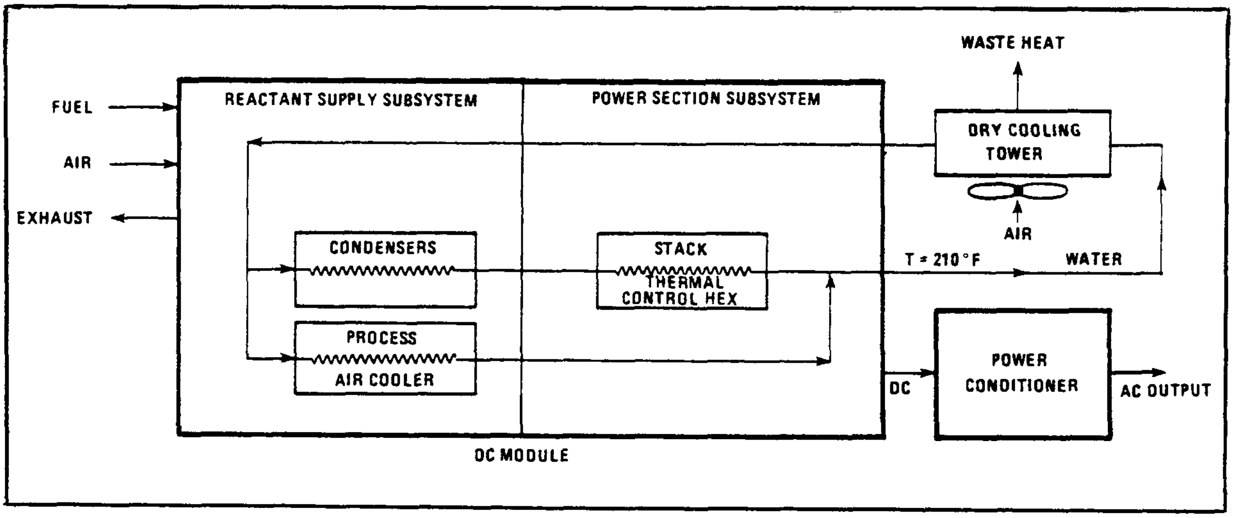

Figure 2-4. Fuel Cell Power Plant Thermal Management Subsystem.

Source: United Technologies Corporation, Reference (<u>2</u>).

Configuration A - Minimum Modifications, Hot Water Only - This configuration is shown in Figure 2-5. Waste heat is recovered from the dc module heat rejection exchangers (water recovery condensers, process air cooler and stack thermal control heat exchanger) in the normal manner by the cooling tower coolant. The coolant, heated to $210^{\circ}F$, can then be pumped to a potential user to flow through this heat recovery heat exchangers instead of through the DCT heat exchangers. If there is no thermal energy demand the coolant flows through the DCT heat exchanger in the same manner as in the baseline electric generator. Controls (not shown in Figure 2-5) regulate the coolant flow rate to maintain the proper fuel cell system temperature over the operating range. To maximize the amount of useful thermal energy, heat is also recovered from the air-supply turbine exhaust.

The total thermal energy available as $210^{\circ}F$ hot water ($80^{\circ}F$ return) is shown in Figure 2-6. At rated power, the total amount of thermal energy available is 4.12 million Btu/hr. per rated MW. Figure 2-6 shows the available energy in the range 25% to 100% of rated electric output and also at idle (standby with zero electric output).

Since only minimal modifications are required, the capital costs are small. UTC has estimated the costs of heat recovery to be about \$2-3 per kW_{ac} (2).

Configuration B - Modification for Hot Water and Steam Availability - This configuration requires more modifications to the baseline TMS and can supply about 20% of the thermal energy as steam at $350^{\circ}F$ (120 psig). The rest of the thermal energy is available as hot water at $160^{\circ}F$. The total heat recovered, however, is the same as that in Configuration A.

Heat recovered from the stack thermal control heat exchanger and the high temperature part of the process air cooler is at a temperature sufficiently high to heat $200^{\circ}F$ return water to $350^{\circ}F$, 120 psig steam. Lower temperature heat is recovered from the other heat rejection heat exchangers in the dc module (water recovery condensers, turbine exhaust heat exchanger, and the low temperature part of the process air cooler) by heating $80^{\circ}F$ return water to $160^{\circ}F$.

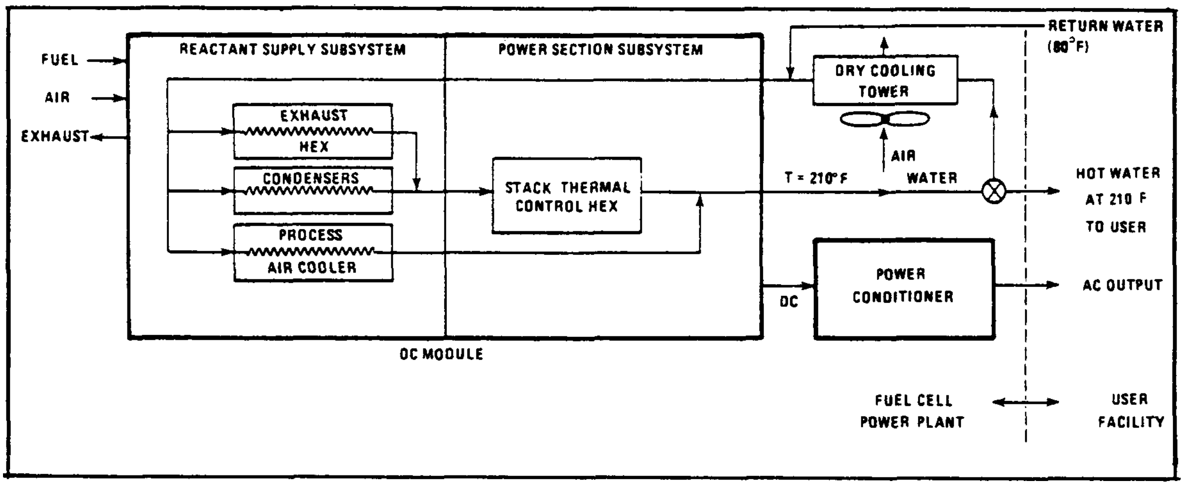

Figure 2-5. Configuration A - Minimum Modifications for Heat Recovery.

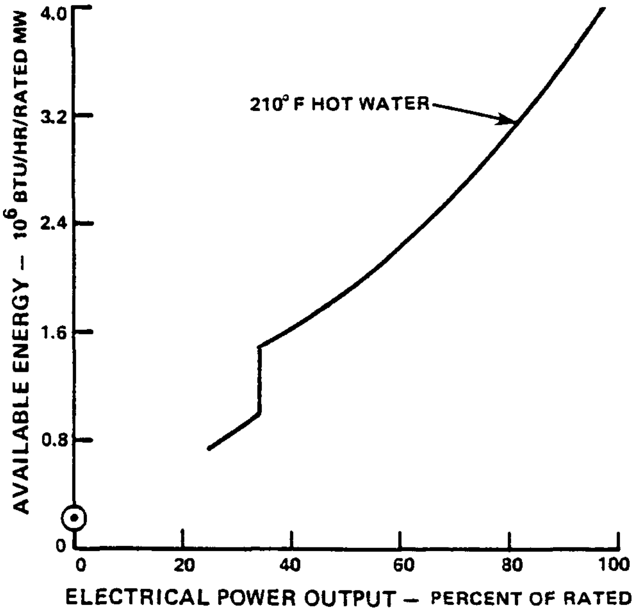

Figure 2-6. Estimated Heat Recovery Capability - Type I Fuel Cell Power Plant with Minimum Modifications (Configuration A)

Configuration B heat recovery is implemented by placing the high temperature and low temperature heat rejection heat exchangers in separate cooling loops with each loop having its own section of the cooling tower exchanger (for use when heat recovery is not required). This is shown schematically in Figure 2-7. In addition, the high temperature DCT loop contains a steam separator to ensure that high quality steam is available to the user. The dc module heat exchangers always operate in the same manner to generate 350°F and 160°F temperatures in their respective loops regardless of whether the heat is recovered or rejected through the cooling tower. Controls (not shown in Figure 2-7) regulate the coolant flow rates to maintain the proper fuel cell system temperatures over the operating range.

Figure 2-8 shows the amount of energy available at each temperature over the 25% to 100% rated electric power load range and at idle (standby). As shown, 0.87 million Btu/hr per rated MW is available as 350°F steam and 3.25 million Btu/hr per rated MW as 160°F hot water at the rated electric output.

This configuration requires three technical changes to accomplish the heat recovery at two levels:

- splitting the cooling tower coolant loop into two loops
- splitting the process air cooler into two heat exchangers
- adding an air-supply turbine exhaust heat exchanger.

The incremental capital cost of these modifications has been estimated by UTC as $13 to 19 per kwac. (2).

Configuration C - Modification for Additional Steam Availability - In this configuration, further modifications are made to generate additional thermal energy over and beyond the thermal energy rejected in the power generation process. This is accomplished by using the power section subsystem startup unit during normal power plant operation. The startup burner is transfered to the cell stack coolant through the startup heat exchanger and recovered in the same manner as the waste heat. Any desired amount of heat can be generated by properly iszing the coolant loop components. This configuration can be further subdivided into 3 options depending on the degree of modification and the amount of additional thermal energy that is needed.

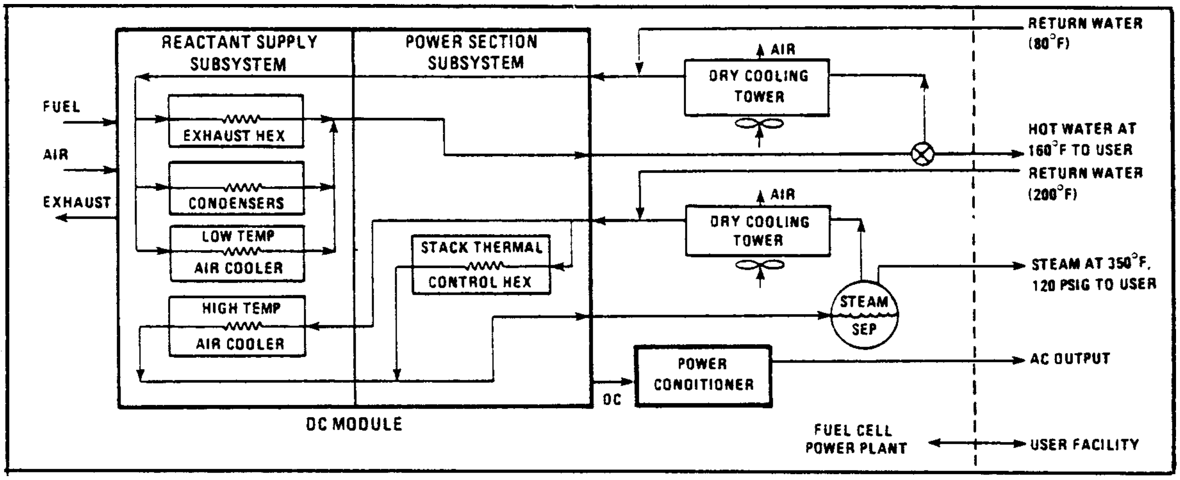

Figure 2-7. Configuration B - Modifications to Make Steam Available.

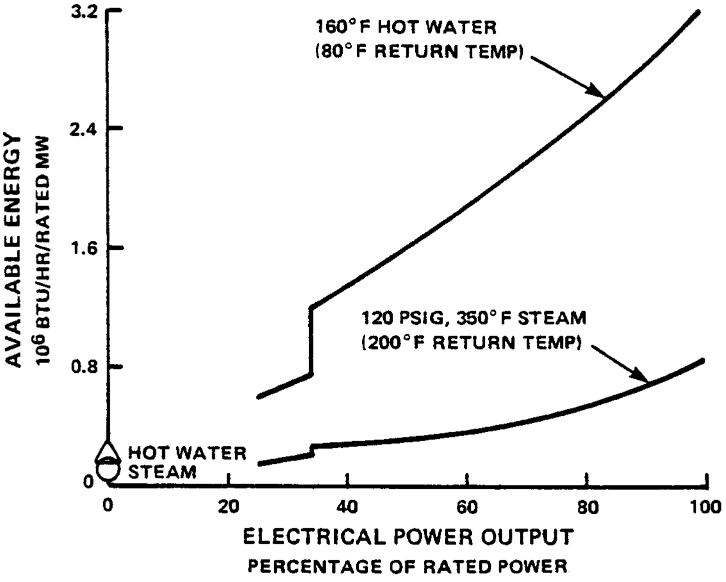

Figure 2-8. Configuration B - Modifications to Make Steam Available.

Option I, as shown in Figure 2-9, requires no modifications to the coolant loop hardware. If the option is used with Configuration B, the additional heat is available as 350^{O}F, 120 psig steam. The total thermal energy output (waste heat plus generated heat) is shown in Figure 2-10 and compared to configuration B. At rated power no additional heat can be generated because the steam separator and stack thermal control heat exchanger, which are sized to handle rated power stack waste heat, are operating at their design capacity.

At lower electric power output the normal load on these components decreases and the burner can be started. At electric power output levels of about 78% of rated and lower, the sum of waste heat and maximum burner heat is equal to or less than the capacity of the steam separator and stack thermal control heat exchanger. In this power output range the startup burner operates at its rated capacity and limits the amount of <u>additional</u> heat generation to 0.35 million Btu/hr per rated MW. If this option is used in conjunction with Configuration A, this same amount of additional energy is available as 210^{O}F hot water. No cost differential was calculated since the only modification required for this option involves control logic to allow operation of the burner when additional heat is needed. The efficiency of the additional heat generation is 53% with the baseline electric generator components.

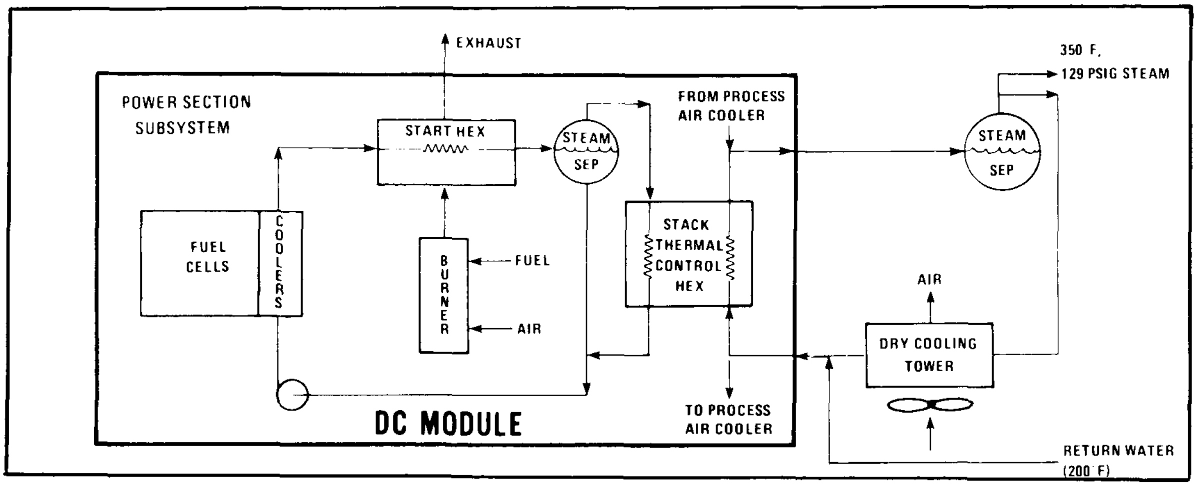

Figure 2-9. Configuration C - Additional Steam Available; Option I - No Modifications to Power Plant.

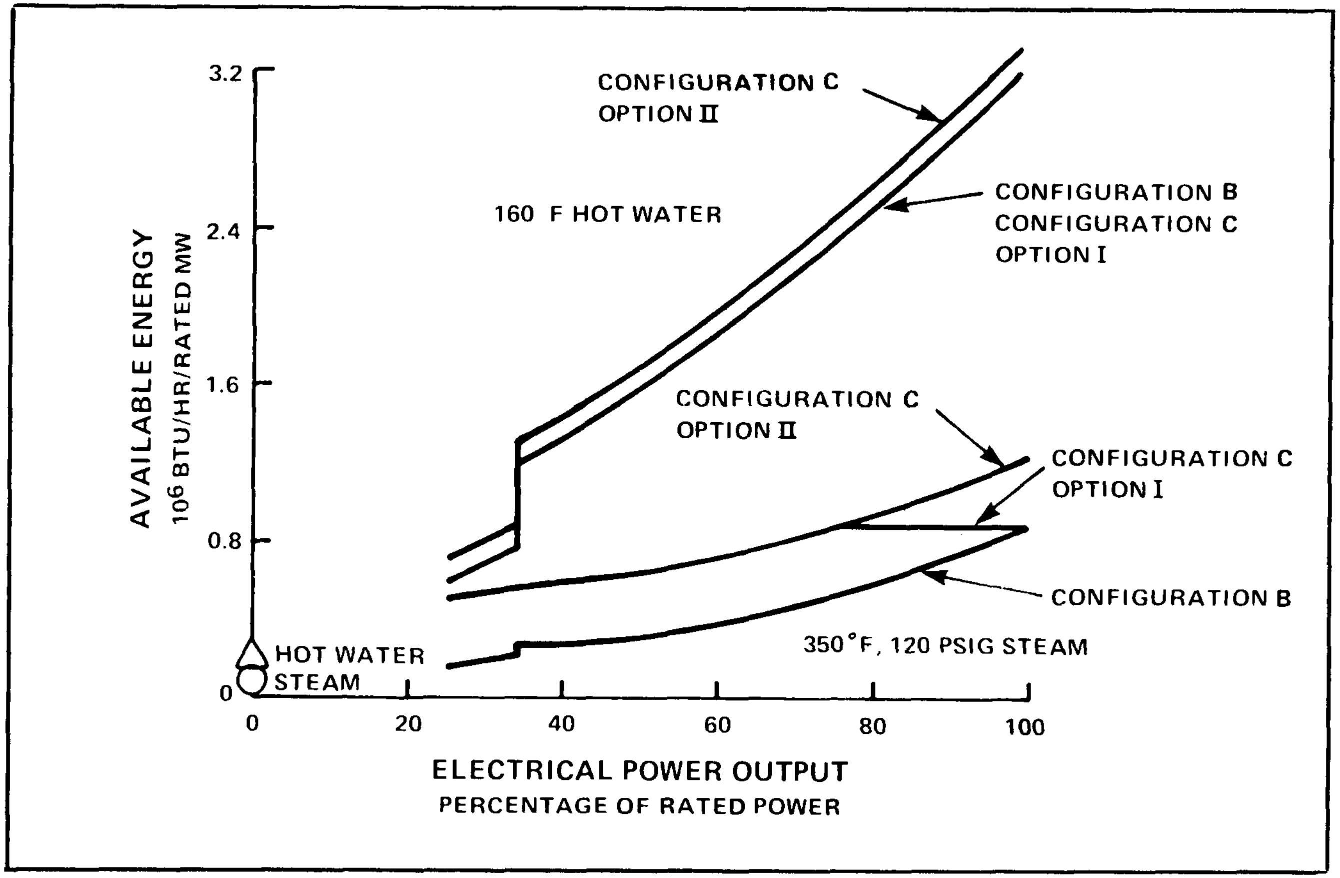

Figure 2-10. Estimated Heat Recovery Capability: Type I - Phosphoric Acid Fuel Cell Power Plant with Additional Steam Available

Option II, as shown in Figure 2-11, results by making two modifications to Option I. In the first modification, the steam separator and stack thermal control heat exchanger are enlarged to match the baseline burner capacity. This allows the burner to operate at its rated capacity over the entire electric power output range and increases the rated power output of thermal energy as steam to 1.2 million Btu/hr per rated MW as shown in Figure 2-10.

In the second modification, a burner exhaust heat exchanger is added downstream of the startup heat exchanger to recover more of the burner heat. This exchanger heats 80°F return water while cooling the exhaust and increases the total energy available as 160°F hot water at rated power to 3.38 million Btu/hr per rated MW. This also increases the efficiency of the additional thermal energy generation to 84%. The estimated cost differential to incorporate this option into a power plant that has already been modified to Configuration B is about $\$1/kW_{ac}$ (2).

Option III results by enlarging all the components in the coolant loop (startup burner, startup heat exchanger, steam separator, stack thermal control heat exchanger and burner exhaust heat exchanger), to meet the desired thermal output. If only additional 350°F energy

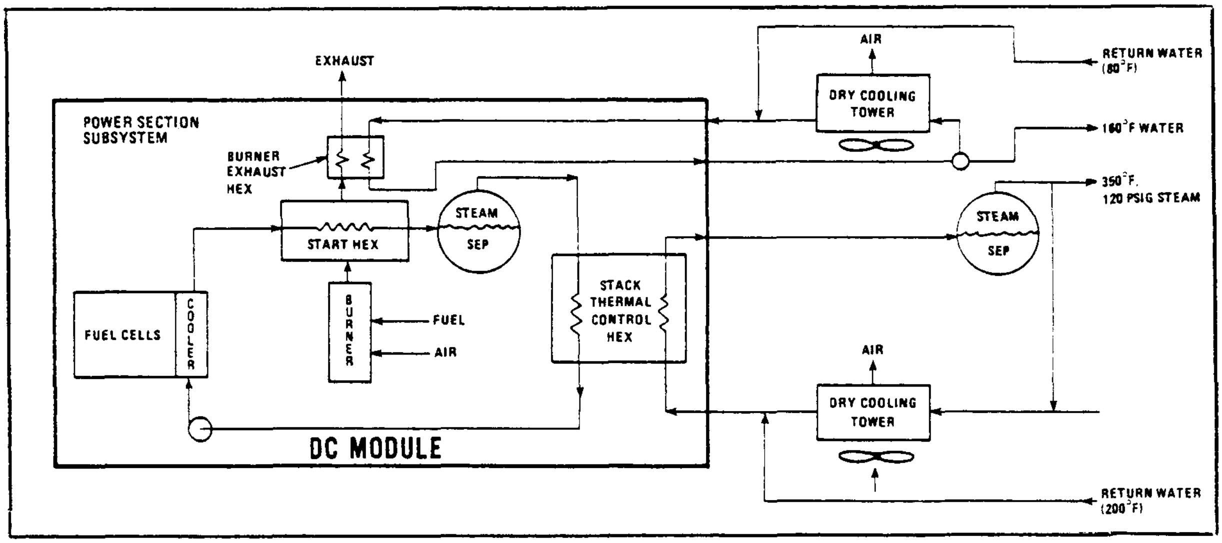

Figure 2-11. Configuration C - Additional Steam Available; Option II - Larger Thermal Control HEX & Steam Separator.

is desired, the exhaust heat exchanger is not enlarged and Option IIIA results. Figure 2-12 shows the estimated cost differential as a function of additional thermal energy. No fundamental limit to the allowable size increase was identified but as these components get larger and larger they become more and more like a packaged boiler. Because of the uncertainty of scaling these components over a large size range, the cost curve (Figure 2-12) is drawn solid to 1.5 million Btu/hr per rated MW which represents a factor of four increase in startup burner size. The curve is dashed to 5 million Btu/hr per rated MW, which represents a factor of about six increasein total energy output as 350°F steam. This figure should be used as a trend curve. No other components of the power plant are affected. The larger burner in this option generates high temperature gas (2000°F instead of 1250°F in the baseline module) and the start HEX is integrated into the steam separator to accomodate the higher temperature gas. This increases the efficiency of the additional thermal generation (as 350° steam) to 74%.

If additional thermal energy as 160°F hot water is also desired, the

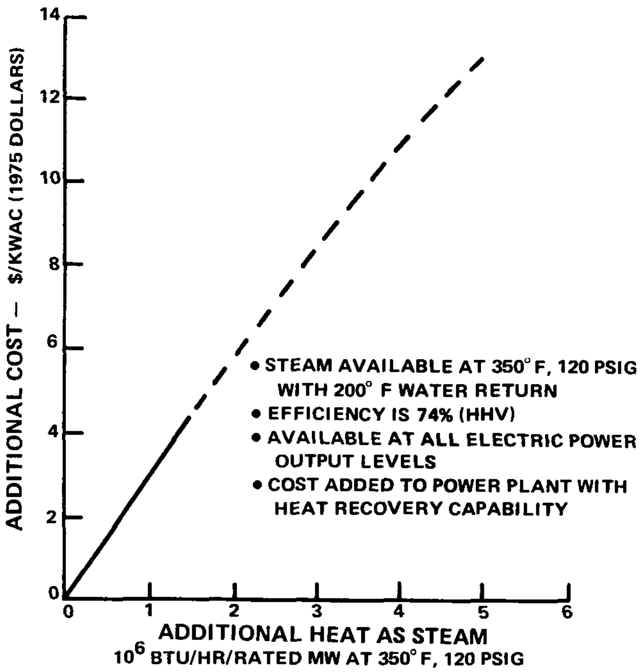

Figure 2-12. Estimated Cost of Additional Heat Recovery - Option IIIA, Configuration C.

exhaust heat exchanger downstream of the startup heat exchanger is also enlarged and Option IIIB results. Figure 2-13 shows the amount of additional energy available and the incremental cost for recovering it. By recovering this additional heat from the burner exhaust, the overall efficiency of the additional thermal energy generation (additional steam plus additional hot water) is increased to 87%.

Alternate Approach with Electric Heaters

Another technically feasible alternative for additional thermal energy is the use of electric heaters. Figure 2-14 shows this configuration, which can provide for flexibility to satisfy a wide range of thermal/electric demand ratios, and requires no modifications to the baseline power plant equipped with heat recovery capability. The power plant efficiently generates electricity that can be used to produce steam or hot water in an external boiler at practically any temperature desired. A single installation (power plant plus electric heaters) can provide a range of electric/thermal outputs from rated electric and reject thermal to no electric and 100% thermal (reject heat plus heat generated by rated electric output), all for the same high overall fuel utilization shown in Figure 2-1. Heaters can either be

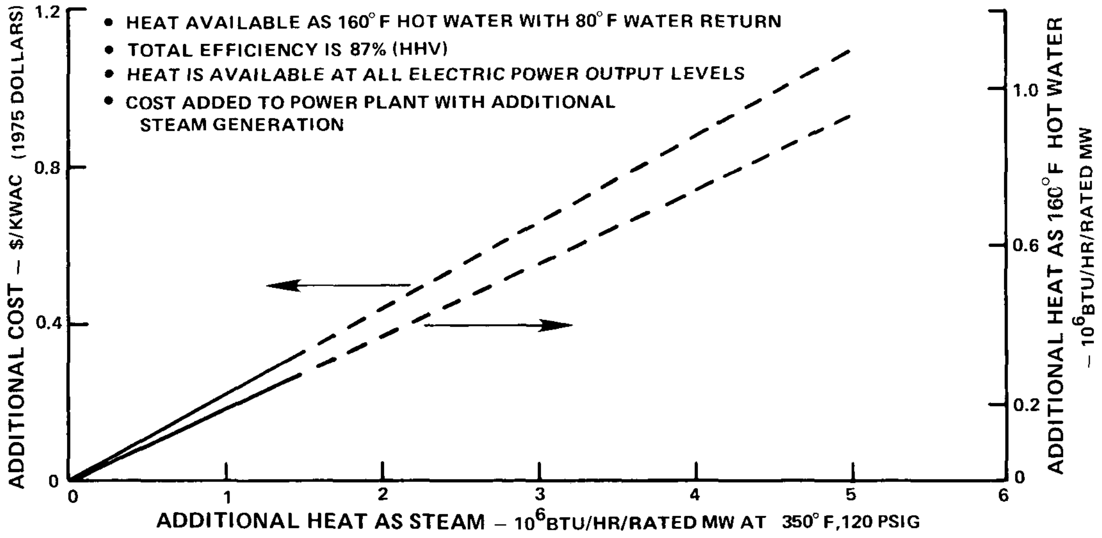

Figure 2-13. Estimated Cost of Additional Heat Recovery - Option IIIB, Configuration C.

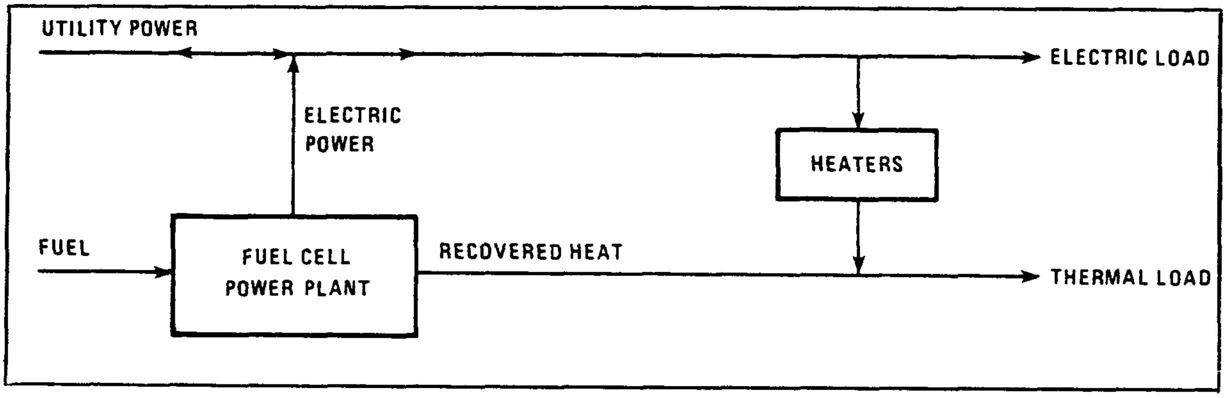

Figure 2-14. Alternate Approach - Use of Electric Heaters with Baseline Fuel Cell Power Plant.

incorporated into the thermal management loop or heat recovery system of the power plant, or can be a separate electric boiler unit. A separate electric boiler unit allows the flexibility of providing thermal energy at any desired temperature while thermal energy generated by heaters within the power plant is delivered at the same temperature as the power plant reject heat.

However, the economics of this option are questionable at best. The value of thermal energy for the range of promising applications considered appeared to be no more than $5.00 per million Btu (see Sections 4-6). The value of electricity, using the incremental generation cost in off-peak periods is at least 20 mills per knh (see Sections 4-6) or about $6.00 per million Btu. Therefore the use of electricity to generate thermal energy is economically undesirable. This alternative approach was therefore not investigated further.

MAINTENANCE, STARTUP AND SHUTDOWN FOR TYPE I POWER PLANTS

Additional information required for evaluation of DEUS fuel cells included estimated scheduled maintenance interval and downtime, and energy consumed during startup, shutdown and idle operation.

Scheduled Maintenance

Table 2-1 shows the estimated maintenance requirements for DEUS fuel cells based on projected capabilities of developed technology and hardware. Maintenance interval estimates for all maintenance actions, except cell stack assembly replacement are based on continuous operation at an average of half power. A five year interval for cell stack assembly replacement assumes the cells are held at operating temperature for that period (2).

Maintenance costs are estimated to be $0.26/kw per year fixed cost and 2.85 mills/kw-hr per year variable cost. These are the estimates that were used earlier by PSE&G (3) and in small utilities by Burns and McDonnell (4). UTC has estimated that these maintenance costs will not change for the different configurations listed above for heat recovery.

Startup,Shutdown and Idle Characteristics

Table 2-2 shows the time and energy requirements for startup, shutdown and idle operation (standby with no power output). These estimates are based on the 4.5 MW Demonstrator, and UTC describes these as conservative (2). Startup of a non-operating power plant at 70°F ambient temperature takes about four hours and is estimated to consume 1500 lbs. of fuel (30 million Btu, HHV) to heat the power plant. In addition, 775 kwh of electic energy is required to operate the electrically driven components in the power plant.

Table 2-1

ESTIMATED MAINTENANCE REQUIREMENTS FOR DEUS FUEL CELLS

INTERVAL	ESTIMATED DOWNTIME	MAJOR MAINTENANCE ACTION
1 YEAR	2-3 DAYS	REPLACE HYDROTREATER ABSORBENT BED (INTERVAL VARIES WITH LOAD PROFILE AND SULFUR CONTENT OF FUEL)
>2 YEARS	2-3 WEEKS	REPLACE FUEL PROCESSOR CATALYST
5 YEARS	2-3 WEEKS	REPLACE CELL STACK ASSEMBLIES
10 YEARS	3-4 WEEKS	OVERHAUL REFORMER, CONTROLS, WATER TREATMENT SUBSYSTEM, COOLING TOWER AND BURNERS

Table 2-2

STARTUP, SHUTDOWN AND IDLE CHARACTERISTICS - 4.5 MW DEMONSTRATOR

	TIME – HRS	FUEL CONSUMPTION	ELECTRIC – KWHR
STARTUP	4	30×10^6 BTU (1500 LB FUEL)	775
SHUTDOWN	15	—	1475
IDLE (NO ELECTRIC OUTPUT)	—	6×10^6 BTU/HR (300 LB/HR FUEL)	165-KW

A shutdown consists of removing the electric load, inerting the power plant and cooling the fuel cells. Studies on the 4.5 MW Demonstrator indicate this overall process will take 15 hours and consume 1475 kwh of electric energy. Estimated energy consumption during idle (standby with zero electrical output) is 300 lb/hr fuel (6 million Btu/hr, HHV) and 165 kw electric power. In this condition all components are at their respective operating temperatures and the power plant is ready to go on load.

Much of the startup time and energy is associated with heating the fuel processing subsystem beds and the fuel cell stacks to their respective operating temperatures. Therefore a restart, when these components have not yet cooled to ambient temperature, requires less time and energy then shown in Table 2-2. Time and energy required to restart the power plant as a function of cooldown time is shown in Figure 2-15. This shows that time and energy to restart after cooldown times of 1-2 days are considerably less than for startup after the entire power plant has cooled to ambient conditions.

TYPE II-MOLTEN CARBONATE FUEL CELL POWER PLANTS

The Type II-molten carbonate fuel cells are expected to be commercially available in the mid to late 1980's. The goal of the current research and development efforts is to develop a dispersed power plant with a heat rate of 7500 Btu/kwh at costs comparable to those of Type I fuel cells. The performance potential of configurations suitable

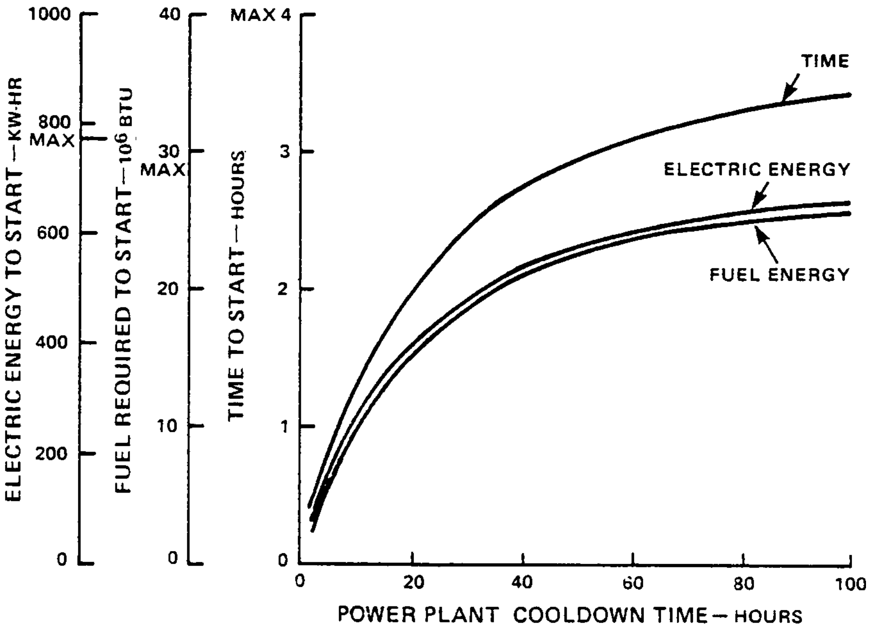

Figure 2-15. Effect of Cooldown Time on Power Plant Startup.

for power plant use has been demonstrated. However, demonstrations of improved endurance and performance are required to establish the basis for engineering development. (5)

A schematic diagram of the system concept for a molten carbonate fuel cell is shown in Figure 2-16. Some of the significant differences between the two types are:

- the fuel processor in Type II is simpler
- water is removed only at the anode, permitting smaller and lower cost condensers and simplifying controls.
- cell operates at a higher temperature.

The last factor allows for some higher grade thermal energy to be recovered and utilized from the Type II cell. Since the cell operates at a temperature in excess of 1100°F, some thermal energy can be recovered as high pressure steam at 1035 to 1060°F. However, the quantity of thermal energy available as steam at this level is only about 4% of the input fuel energy. An approximate energy balance for a hypothetical Type II cell is shown in Figure 2-17. This figure shows thermal energy available <u>before</u> any heat exchangers and therefore overstates the <u>usable</u> thermal energy by about 10 to 15%.

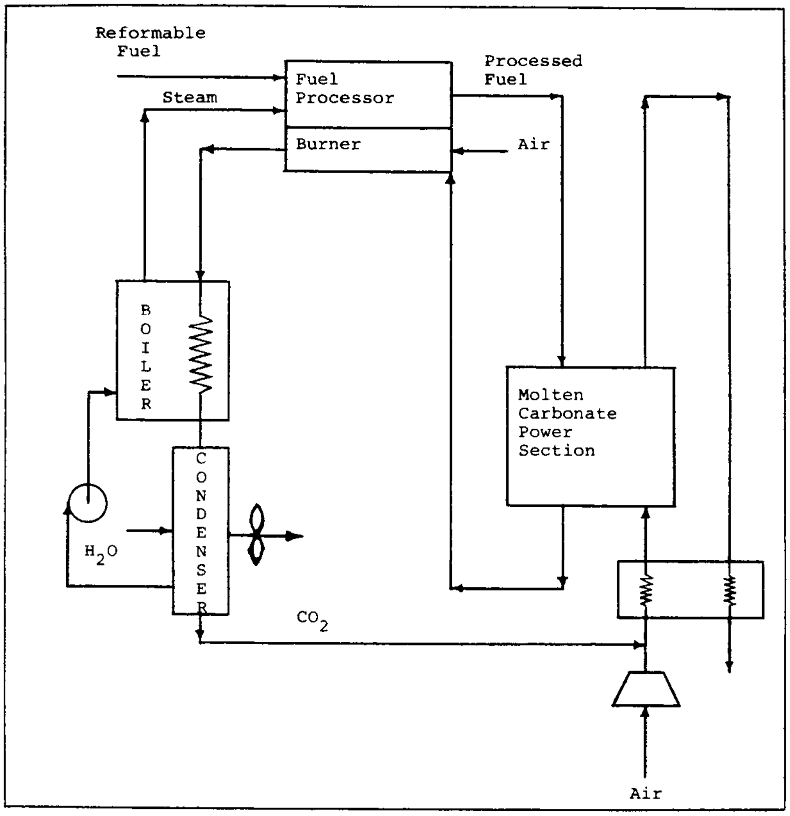

Figure 2-16. System Schematic - Type II Molten Carbonate Fuel Cell.

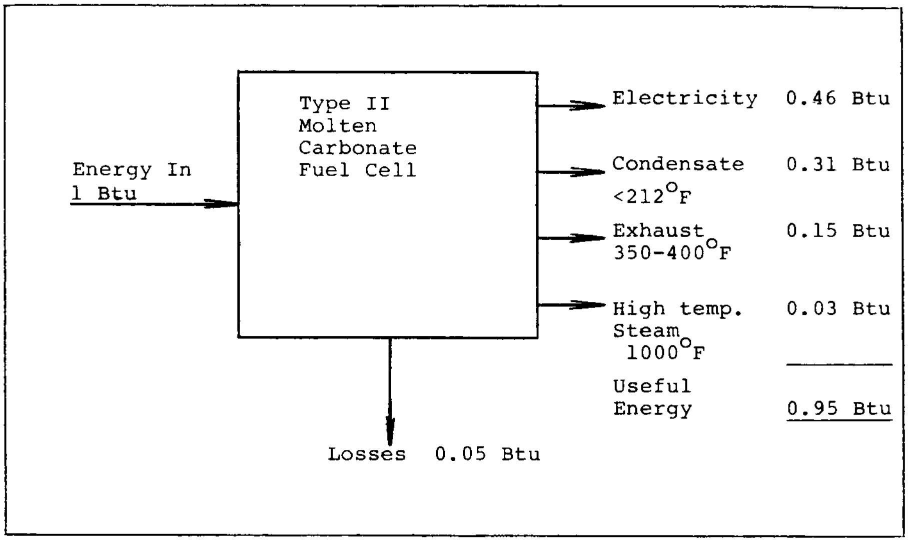

Figure 2-17. Approximate Energy Balance for Type II Fuel Cell.

Figures 2-18 and 2-19 show the I/O and heat rate characteristics, respectively, of the Type II fuel cell at different electric output levels.

At rated power, the Type II fuel cell can produce 2.3 million Btu at 165°F, 1.1 million Btu at 373°F and only about 0.3 million Btu at 1038°F per MW of electic output. If all these streams are mixed, the total is 3.7 million Btu at an average temperature of about 298°F. This compares to 4.1 million Btu at an average temperature of about 210°F from the Type I fuel cell.

While the quantity of thermal energy available at the highest temperature (1000°F) from the Type II fuel cell is very small, it does offer the potential for application to thermal loads requiring higher quality heat. For example, the mixing of the two higher temperature streams gives an average temperature of 515°F, with about 1.4 million Btu per MW available at this temperature. Since the maximum quality of thermal energy available from the Type I cell is 350°F, the Type II cell does offer an advantage in that applications requiring thermal energy in the 350 to 500°F may be feasible for Type II DEUS fuel cells.

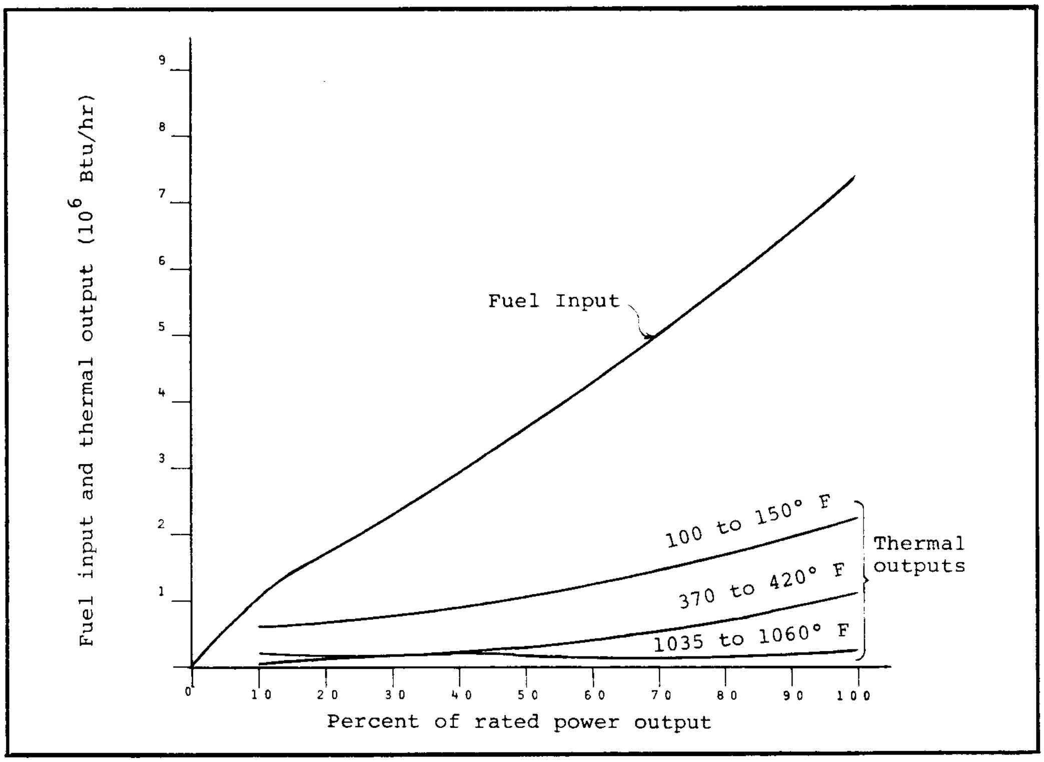

Figure 2-18. Type II (Molten Carbonate) Fuel Cell Characteristics (Expressed for hypothetical 1 MW cell module)

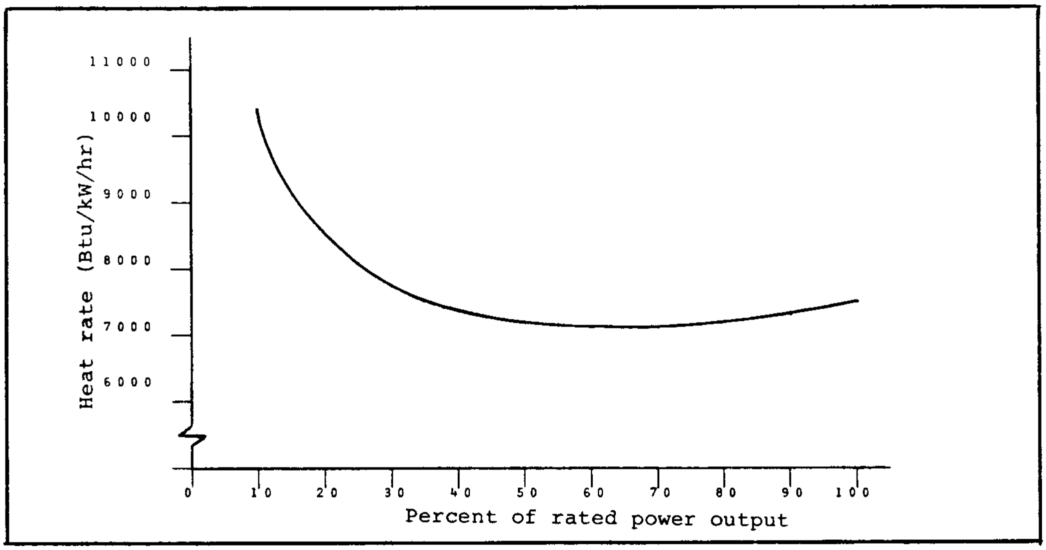

Figure 2-19. Heat rate vs. Electrical Output for Type II Molten Carbonate fuel cell power plant.

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2. United Technologies Corporation, Characteristics of Type I Fuel Cell Power Plants in Dual Energy Use Systems (DEUS), Final Technical Report, submitted to Mathtech Inc., 1978.

3. Public Service Electric and Gas Company, Economic Assessment of the Utilization of Fuel Cells in Electric Utility Systems, EPRI EM-336, Final Report, November 1976.

4. Burns and McDonnell Engineering Company, An Assessment of the Fuel Cell's Role in Small Utilities, EPRI AF-696, Final Report, Volume 1, February 1978.

5. United Technologies Corporation, Advanced Technology Fuel Cell Program, EPRI EM-335, Final Report, October 1976

Section 3

DEUS EVALUATION METHODOLOGY

As indicated in Section 1, a number of building system, industrial and utility energy consumers were selected as potential applications for the types of DEUS fuel cells described in Section 2. Before these applications could be evaluated, however, it was necessary to answer a number of questions, including

- Which conventional systems should DEUS fuel cells be compared to?
- What DEUS plant designs and operating strategies should be evaluated?
- What is a meaningful measure of DEUS plant economic performance?
- How should the energy supply impact of a fuel cell DEUS be assessed?

The following four subsections address each of these questions in turn. The combined answers form a basis for the analyses described in Sections 4 through 6.

BASIS FOR COMPARISON

One of the most critical determinations in evaluating any energy conversion alternative is the selection of the base system(s) to which the alternative will be compared. For utility-owned, DEUS fuel cells the most likely base systems included:

- conventional base load plants
- conventional intermediate load plants
- conventional peak load plants
- other fuel cells
- some combination of the above

The obvious problems in comparing DEUS fuel cells with conventional utility generation are, of course, that the various plant types generally have different sizes, sites, fuels, and capital and operating costs. Thus, in any comparison it would be difficult to determine whether longterm differences in performance were attributable to DEUS operation or to the basic differences in technologies. Further, studies here have already been performed by Public Service Electric & Gas Company (1) and Burns and McDonnell, Inc. (2) that compare fuel cells with conventional types of operation. An important finding in both studies was that fuel cells achieve significant penetrations into future utility power resource mixes, regardless of whether a heat recovery capability is included. Because of these previous findings, therefore, and the added complexities of comparing totally different technologies, it was decided to focus on the specific costs and benefits of fuel cell reject heat utilization and compare the DEUS fuel cell selected for each application with a conventional (electric-only) fuel cell of the same size.

DEUS DESIGNS AND OPERATING STRATEGIES

A basic difference between DEUS and conventional fuel cell power plants is that the DEUS plant must satisfy demands for both thermal and electrical energy while the conventional fuel cell plant supplies only electricity. Depending on the specific application at hand, the requirements for thermal energy and electricity from the DEUS plant may be totally disproportionate or may not occur at the same time. Thus, if both demands are to be satisfied, methods must be devised for matching them with respect to size and decoupling them with respect to the time at which they occur. Such matching and decoupling can be accomplished in two ways:

- through DEUS plant design modifications, e.g. the addition of supplemental boilers or thermal storage
- through the selection and specification of alternative plant operating strategies.

For the purposes of this study, a specific combination of a DEUS plant design and an operating strategy is referred to as a "load matching/decoupling option." The specific DEUS designs, and therefore options, considered vary to a large degree according to the class of applications that is being considered. Therefore, these are discussed in the Sections 4 through 6, which describe the building system, industrial, and utility applications analyses respectively.

The basic plant operating strategies, however, are used in all three analyses and are discussed below. For any power plant that supplies electrical and thermal energies, the two extreme operating strategies are obvious:

- Electric (or Economic) Dispatch, in which the plant operating level is determined by the demand for electricity and thermal energy is produced strictly as a by-product.
- Thermal Dispatch, in which the plant operating level is determined by the demand for thermal energy and electrical energy is strictly a by-product.

In this case, of course, "electric dispatch" must be defined carefully,since the DEUS plant is utility-owned and grid-connected and the "grid" serves as both a consumer and a supplier of electricity. It does not follow, however, that the utility is insensitive to the times at which the DEUS plant generates electricity. On the contrary, most utilities operate their generation in accordance with elaborate dispatch schedules, determined so as to minimize system production costs. A given power plant's economic dispatch schedule specifies both its periods of operation and its instantaneous operating level over some scheduling interval. Approximate economic dispatch schedules for the reference utility (described in Section 1) were determined as illustrated in Figure 3-1 from fuel cell fractional weekly loadings, utility load duration curves, and daily load profiles. It was assumed that the reference utility would typically operate these plants as intermediate load generation for approximately 13 hours out of a typical weekday. Typical start and stop times for fuel cell plants are 7 a.m. and 8 p.m., respectively. In the analyses that follow, these were the approximate operating hours (henceforth called the "on-peak" hours) assumed for all conventional fuel cell plants. Conventional plants are assumed to operate at full load when "scheduled" and to operate at the fuel cell equivalent of spinning reserve (25% electrical output*) at all other times (henceforth called the off-peak hours). This manner of operation is justified by the

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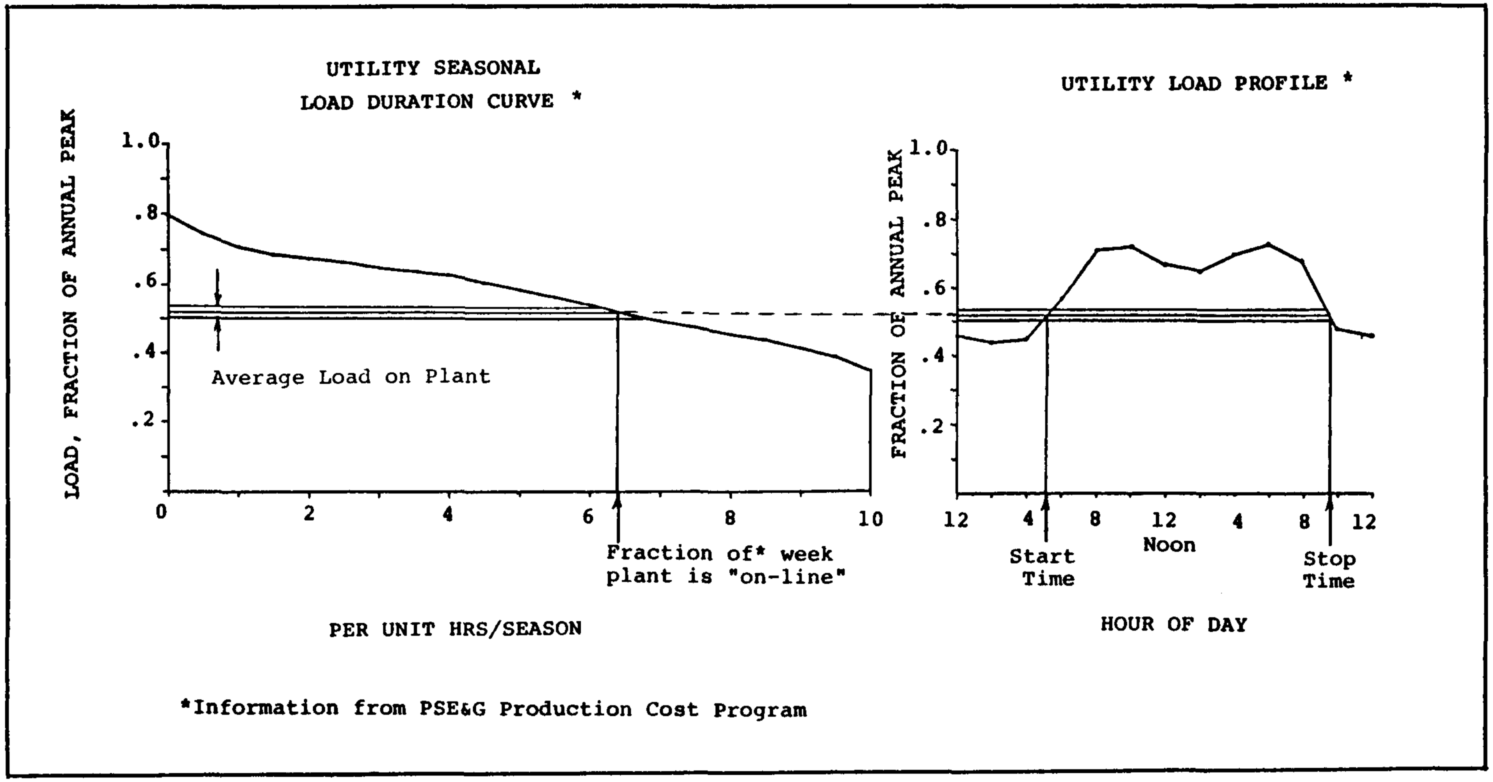
* The technical characteristics of operating a fuel cell at 25% power were described previously in Section 2.



*Information from PSE&G Production Cost Program

Figure 3-1. Procedure for Estimating Typical Load Schedules for a Conventional Plant Typical Weekday in Winter high costs of fuel cell startup and shutdown and the benefits to the utility of additional spinning reserves.

Since it is assumed that the reference utility operates conventional fuel cells according to economic dispatch, it is also assumed that the utility would prefer to operate DEUS fuel cells in the same manner. Economic dispatch, therefore, is one operating strategy under which fuel cell dual energy use systems and conventional fuel cells were compared. Of course, it cannot be assumed that electric dispatch is either the most economic or the most efficient way to operate a DEUS plant that also benefits from the supply of thermal energy. In order to evaluate operation "at the other extreme," therefore, thermal dispatch was also selected as a DEUS operating strategy for comparison with the conventional fuel cell (operating under economic dispatch). Many other DEUS operating strategies that combine elements of straight electric and thermal dispatch are also possible, and some of these are evaluated in the analysis that follow. Because of their simplicity, however, economic and thermal dispatch were selected as the baseline DEUS operating strategies for all classes of applications.

ECONOMIC EVALUATION

The key criterion in establishing an index of DEUS fuel cell economic performance was that the index must consider only the economic differences between DEUS and conventional fuel cells. In previous studies (1, 2) breakeven capital costs for utility-owned fuel cells had already been defined. Therefore, it was decided to evaluate the change in fuel cell breakeven capital costs when reject heat is utilized. This index, which is called the incremental breakeven capital cost (abbreviated ΔBECC), is the amount by which the DEUS fuel cell's capital cost can change from that of a conventional fuel cell without affecting the life cycle cost of owning and operating a fuel cell power plant. If this index is positive and greater than the capital cost of any fuel cell heat recovery modifications that might be required, the concept of a fuel cell DEUS would appear to be a good one.

For the purposes of this study the incremental breakeven capital costs was defined as

$$\Delta BECC = \left\{ \frac{T_{cr} - \Delta P - \rho}{E_{cap} \cdot CC \cdot CCIF} \right\} - C_{aux} \qquad (3\text{-}1)$$

where T_{cr} = annual credits resulting from the sale of thermal energy

ΔP = annual production cost increase due to DEUS operation

ρ = annual total of all penalty costs incurred by DEUS plant deviations from economic dispatch operation

E_{cap} = capacity of fuel cell (kW)

CC = construction compound interest factor (1.05 for a fuel cell)

C_{aux} = capital cost of all DEUS plant auxiliary systems, normalized by fuel cell capacity ($/kW)

This equation is based on the assumption that annual costs and thermal energy sales are constant for each year in a 20-year study period. A full derivation of Equation 3-1, including a list of all implicit assumptions, is provided in Appendix B.

If the cost of heat recovery is deducted from the value of ΔBECC as defined above, it is possible to calculate a "net credit" to the fuel cell for reject heat utilization. That is,

$$\text{Net Credit for Heat Utilization} = \Delta BECC - C_{HR} \qquad (3\text{-}2)$$

Where C_{HR} is capital cost of all heat recovery modifications made to the DEUS fuel cell ($/kW).

In the application analyses described in Sections 4 through 6, ΔBECC is taken as the primary economic index. In some instances, The Net Credit for Heat Utilization may also be presented to show the relative magnitudes of the various capital costs involved. Table 3-1 provides an example of these various capital cost indices for a 13.5 MW DEUS plant, including a fuel cell and boiler, that supplies the entire thermal load of a one million square foot hospital in New Orleans, Louisiana. Since in this example the plant is assumed to operate according to economic dispatch, the penalty costs (for deviations from economic dispatch) are zero. The total increase in annual production costs is due, in this case, to the combined costs of fuel and operation and maintenance for the supplemental boilers.

In order to get a better "feel" for the range of values of ΔBECC that may result in the analyses of specific DEUS applications, it is useful to derive some hypothetical maximum and minimum values for this index. Assuming an economically-dispatched 4.5 MW DEUS fuel cell with no auxiliaries,

$$\Delta BECC = \frac{T_{cr}}{E_{cap} \cdot CC \cdot CCIF} = \frac{T_{cr}}{(4500\ kW)\ (.189)} \qquad (3\text{-}3)$$

The maximum ΔBECC will occur when the thermal load profile of the application is completely synchronized with the economic dispatch requirement of the utility, in which case the plant would supply approximately 277 million Btu's of thermal energy per day and 101 billion Btu's per year (assuming 365 "ideal days"). If a thermal energy value of $3.50 per million Btu's is assumed, the annual thermal credit to the DEUS fuel cell would be 354 thousand dollars and from Equation 3-8,

$$\Delta BECC_{max} = \frac{\$354 \times 10^3}{(4500\ kW)\ (.189)} = 416\ \$/kW \qquad (3\text{-}4)$$

The minimum value of ΔBECC for the same plant under economic dispatch would be 0 $/kW, assuming no thermal energy was actually supplied. In this case, of course, there would be no need to modify the fuel cell for heat recovery. If, on the other hand, only a small fraction of the plant's heat is required or the value of thermal energy is very low, ΔBECC will also be very small and may be less than C_{HR},

Table 3-1

SAMPLE RESULTS OF DEUS FUEL CELL ECONOMIC EVALUATION FOR A LARGE HOSPITAL

DATA ITEM	VALUE
Size of Fuel Cell (kw)	13,500
Annual Thermal Credit, T_{cr} (10^3 \$)	1,272
Annual Production Cost Increase, ΔP (10^3 \$)	513
Annual Penalty Costs, ρ (10^3 \$)	0
Cost of Boiler, C_{aux} (\$/kw)	78
Incremental Breakeven Capital Cost of DEUS Fuel Cell, ΔBECC (\$/kw)	219
Cost of Heat Recovery Modifications to Fuel Cell, C_{HR} (\$/kw)	3
"Net Credit" for Reject Heat Utilization (\$/kw)	216

the cost of heat recovery. In this case, the net credit for reject heat utilization will be negative.

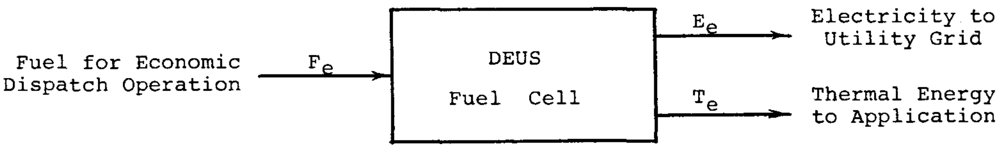
Under thermal dispatch operation, considerably higher and lower values of ΔBECC are possible for two reasons:

- the DEUS plant could conceivably operate at full level at all times, resulting in a large annual thermal credit.
- the DEUS plant incurs penalty costs for all deviations from economic dispatch operation, and such penalties can result in negative values of ΔBECC.

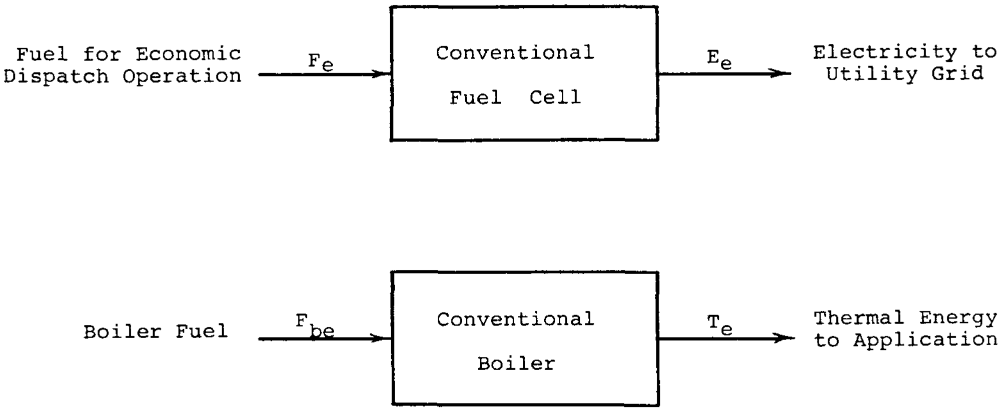
DEUS penalty costs are incurred in the following ways. During on-peak hours the DEUS plant is penalized for operating at less than its full load output, and during the"off-peak" hours the plant is penalized for operating at a level higher than 25% of full load. At any given time, the penalty cost is equal to the amount of power produced under such conditions times the additional unit cost to the utility of producing the power. This additional cost is equal to the absolute difference between the fuel cell's incremental production cost and the utility system's incremental production cost. The annual penalty cost ρ in Equation 3-5 is simply the sum of these hourly penalty costs for each day in the year. If a 4.5 MW DEUS plant operates at full load at all times an annual thermal credit of 567 thousand dollars and an annual penalty cost of 49.3 thousand dollars is incurred. This results in a maximum value of ΔBECC for thermal dispatch operation of 609 $/kW.

ENERGY SUPPLY IMPACT ASSESSMENT

In assessing the energy supply implications of DEUS versus conventional fuel cell operation, two comparisons are made. First, the energy supply efficiencies of these two plant types are compared; then a comparison is made of the total annual energy resources saved by DEUS vs conventional fuel cell operation for a given application. As Figure 3-2 shows, for a DEUS plant that operates according to economic dispatch, the comparisons are straight-forward. Both fuel cells produce the same amounts of electricity at the same time, and use the same amounts of fuel in doing so. Since alternative energy supply comparisons generally require that each alternative system provide the same energy outputs, it is assumed that the



a.) Fuel Cell - Based DEUS



b.) Conventional Fuel Cell Power Plant and Thermal Supply System

Figure 3-2. Annual Energy Supply Comparison Under Economic Dispatch.

conventional system includes a boiler that produces the same amount of thermal energy as the DEUS plant at an average efficiency of 83%.* Using the symbols defined in Figure 3-2, the efficiencies of the DEUS and conventional plants are, respectively,

$$\eta_{DEUS} = \frac{E_e + T_e}{F_e} \tag{3-5}$$

and

$$\eta_{CONV} = \frac{E_e + T_e}{F_e + F_{be}} \tag{3-6}$$

As Figure 3-3 shows, the energy supply comparison is more complicated when the DEUS plant is thermally dispatched. In this case, the DEUS and conventional fuel cells generally produce different amounts of electricity at different times. In order to keep the system electrical outputs equal for the purposes of comparison, therefore, it was assumed that any deficit would be made up with power from the utility grid. The efficiency of generation and delivery of this electricity was assumed to be 29.7% based on figures used by the National Bureau of Standards in a previous study of alternative energy systems (3). Based on these assumptions energy supply comparisons were made as follows for the cases described below.

Case I - DEUS Electrical Production Exceeds Conventional Fuel Cell Electrical Production

In this case, the utility-supplied deficit power, E_u, is credited to the conventional system and

$$E_t = E_u + E_e \tag{3-7}$$

Where E_t is defined in Figure 3-3. Therefore, the DEUS and

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* If the DEUS plant includes a supplemental boiler, its fuel consumption must also be accounted for and a similar efficiency is assumed.

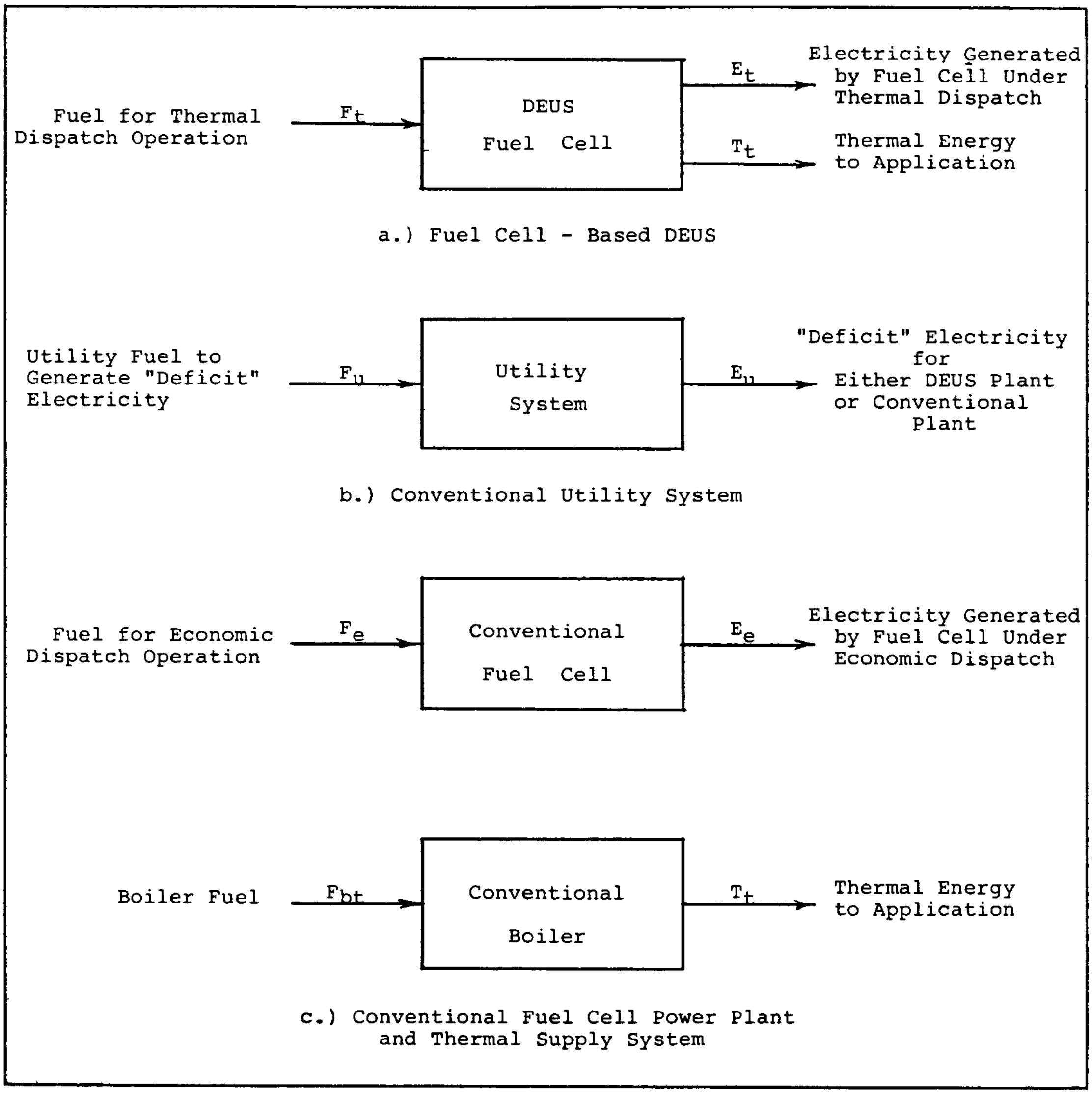

Figure 3-3. Annual Energy Supply Comparison for Thermally Dispatched DEUS Plant.

conventional plant efficiencies are, respectively,

$$\eta_{DEUS} = \frac{E_t + T_t}{F_t} \tag{3-8}$$

and

$$\eta_{CONV} = \frac{E_t + T_t}{F_e + F_{bt}} + F_u \tag{3-9}$$

The annual fuel savings from DEUS operation is

$$(F_e + F_{bt} + F_u) - F_t$$

<u>Case II - DEUS Electrical Production is Less Than (or Equal to) Conventional Fuel Cell Production</u>

In this case, the utility-supplied deficit power, E_u, is credited to DEUS and

$$E_t + E_u = E_e \tag{3-10}$$

Thus, the respective plant efficiencies are

$$\eta_{DEUS} = \frac{E_e + T_t}{F_t + F_u} \tag{3-11}$$

$$\eta_{CONV} = \frac{E_e + T_t}{F_e + F_{bt}} \tag{3-12}$$

The annual fuel savings (loss) from DEUS operation is

$$F_e + F_{bt} - F_t + F_u$$

<u>Type of Fuel Saved</u>

Although the above equations provide a means of calculating the amount of fuel that may be saved by a thermally-dispatched fuel cell DEUS, it is also important to consider the types of utility fuel that are either displaced or consumed as a consequence of deviations from straight economic dispatch. For example, increased off-peak production displaces base load coal and nuclear generation and may result in a savings in coal and uranium but a net increase in the consumption of oil. Decreased on-peak production, on the other hand, tends to necessitate the increased use of peaking units, which not only consume premium fuels but do so less efficiently. Obviously, from an energy resource perspective, the type of fuel saved may be more important than the amount of fuel saved. Therefore, such considerations are are addressed in Sections 4 through 6 whenever the energy impact of thermally-dispatched DEUS fuel cells is assessed.

Section 4

BUILDING SYSTEM APPLICATIONS

SECTION SUMMARY

An analysis of building system thermal energy requirements for space conditioning and domestic hot water was performed. Eight types of building systems were selected for detailed evaluation, and data for representative buildings were developed. Because most space conditioning and domestic water heating requirements can be met satisfactorily using 210°F hot water, all DEUS fuel cells considered for building system applications were assumed to employ Heat Recovery Configuration A, which was described previously in Section 2. DEUS fuel cell systems were examined in both economic dispatch and thermal load following operating modes for each application. In general, it was found that the application of a fuel cell dual energy use systems to building systems is economically viable, except in those instances where the capital cost of a large thermal distribution system is incurred. DEUS facilities can result in a significant savings in the energy required for building space conditioning and domestic hot water production. Specifically, it was found that

- Incremental breakeven capital costs of from $100/kW to $400/kW and DEUS efficiencies of from 60 percent to 80 percent are typical for building system applications.
- Economic dispatch operation of DEUS fuel cells is an economically viable option.
- Thermal dispatch operation is generally more attractive than economic dispatch from both an economic and energy supply standpoint even when on-peak and off-peak penalty costs are included. However, thermal dispatch operation can result in the displacement of less costly, base-load coal or nuclear generation or more extended operation of high cost peaking units.
- Use of supplemental boilers or thermal storage offers additional flexibility in load matching/decoupling and can result in energy savings and higher incremental breakeven capital costs.

- Combinations of economic and thermal dispatch can provide attractive, alternative operating strategies and should be investigated further.
- Higher fuel prices will result in higher incremental breakeven capital costs for a fuel cell DEUS relative to a conventional fuel cell.

This section presents the methodology used in selecting and evaluating such applications and describes the results and findings of this evaluation. First, an extensive list of building types is presented, and the process used in screening these types to obtain a set of promising DEUS applications is described. Then, a number of DEUS plant design and operating options are described. Each option provides an alternative for either matching the thermal output of the DEUS fuel cell to specific building requirements or for decoupling the DEUS thermal and electrical loads. Next, the process of calculating the evaluation indices described in Section 3 is discussed, and major assumptions and data sources are identified. Finally, the results of applying this methodology are presented.

IDENTIFICATION OF POTENTIAL APPLICATIONS

Table 4-1 lists the types of buildings considered for possible DEUS fuel cell application. Also included are mixes of building types, such as those found in a typical residential/commercial strip. If carefully selected, specific building mixes can serve to improve the thermal load profile presented by individual building types. Certain of the listed building types, such as hospitals, which consume large amounts of energy, are obvious possibilities. Others such as single-family developments, which have relatively low energy densities, are intuitively unattractive. The intent in preparing the list, however, was not to rely on intuition and past experience, but to include all major buildings types and mixes and then to reduce the total number of applications using a consistent, step-by-step screening process.

SCREENING PROCESS AND SELECTED APPLICATIONS

A screening methodology was developed to analyze the building applications listed in Table 4-1 and to eliminate those for which the use of DEUS fuel cell power plant is undesirable or infeasible. This methodology, which is illustrated in Figure 4-1, includes consideration of the quality and quantity of thermal energy required, size of the

Table 4-1

BUILDING SYSTEMS CONSIDERED FOR DEUS APPLICATION

Residential Applications	Commercial Applications	Institutional & Other
• Single-Family, Detached Residences • Single-Family, Attached Residences • Multi-Family, Low-Rise Apartments • Multi-Family, High-Rise Apartments • Mixed Residential Zones	• Neighborhood Shopping Center • Commercial Strip • Regional Shopping Center • Central Business District • Office Buildings/Complex • Hotels/Motels • Mixed Commercial Zones	• Hospitals/Medical Complexes • Universities • Military Bases • Primary and Secondary Schools • Correctional Institutions • Airports • Sewage Treatment

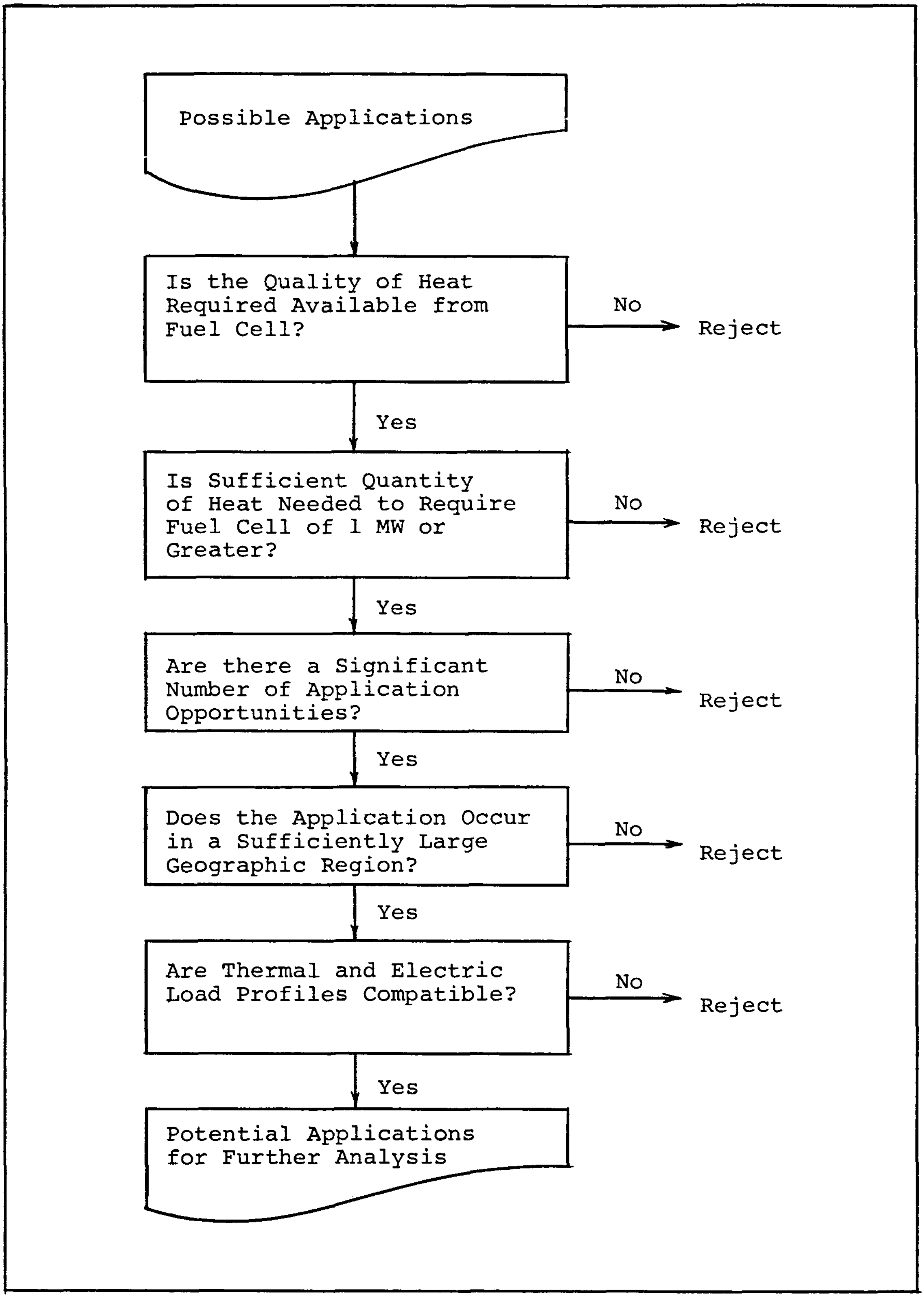

Figure 4-1. Screening Process Flow Chart.

DEUS fuel cell, the number of such applications (nationwide), the sensitivity to geographical location or climate, the coincidence of thermal and electric demands, and the potential value of thermal energy. Specifically, the following questions were asked of each application:

1. Is the quality of heat required by the application consistent with the availability of heat from a fuel cell?

   Thresholds: Only applications that required thermal energy at temperatures less than 210°F were considered for Type I fuel cell application.

2. Do such applications typically require a large enough quantity of thermal energy to utilize the thermal energy produced by a plant of (electrical) capacity of at least 1 MW?

   Thresholds: This analysis was based on estimates of the peak thermal load during a typical weekday in the heating (and/or) cooling season. Applications with thermal requirements less than 1 MW_t were eliminated.

3. Are there enough application opportunities (nationwide) to warrant additional study?

   Thresholds: This analysis subjectively considered the number of potential applications. Only those applications which could be expected to occur in significant numbers in a typical utility's service area were considered.

4. How sensitive is the application to geographical location? When location is considered, is there still a large enough number of application opportunities to warrant futher study?

   Thresholds: The objective was to eliminate applications that would only pass the above screens in a specific geographical region. Because of data limitations the analysis was somewhat qualitative.

5. Is there a satisfactory match between the thermal load profiles for the application and the electric load profiles of typical electric utilities?

   Thresholds: As long as most, or all, of the thermal demand did not occur during generally accepted electric utility off-peak hours, the application passed the screen. For this analysis, the off-peak period was defined to be the interval from 10 p.m. to 6 a.m.

In a limited number of instances where little or no data were available, it was necessary to apply some intuitive judgments in the screening process. In general, however, the available data, coupled with assumptions, were sufficient to support the analyses required at this preliminary screening level. In order to preclude the inadvertent elimination of any promising applications, only those applications that clearly failed one or more of the above screens were rejected without further analysis.

Space heating and cooling, and domestic hot water are the predominant end uses of thermal energy for the building applications considered here. There are, of course, large differences in the amounts of energy required for these purposes and in the temporal profiles.

Each of the applications listed in Table 4-1 was examined in detail and accepted or rejected based on the screening. For those applications that were accepted the analytical results are discussed below.

Residential Applications

An important objective of the residential applications analysis was to determine the numbers of representative types of dwelling units that would be required to provide a typical peak thermal energy demand closely matched to the thermal output of a 1 MW or a 5 MW DEUS fuel cell power plant. Four types of residence (two types of single-family dwellings and two types of multi-family dwellings) were identified as representative of the major classes of residential dwelling units. Typical sizes and constructions for these four dwelling types are summarized* below:

- Single-Family, Detached (SFD):

  One-Story, 1560 ft^2unit; 3 dwelling units per net residential acre.

- Single-Family, Attached (SFA):

  Two-Story Duplex consisting of two 1100 ft^2 units; 10 dwelling units per net residential acre.

- Multi-Family, Low-Rise (MFLR):

  Three-Story, 24-unit garden apartments complex, 900 ft^2 per unit; 15 dwelling units per net residential acre.

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*Sources: Residential and Commercial Energy Use Patterns, 1970-1990, Arthur D. Little, Inc., 1974, modified by Mathtech; and

Costs of Sprawl, Real Estate Research Corporation, 1974, modified by Mathtech.

- Multi-Family, High-Rise (MFHR):

  Ten-Story building, six units per floor, 900 ft^2 per unit; 30 dwelling units per net residential acre.

Since most communities include a mixture of housing types, it was necessary to examine the implications of such mixtures on the number of dwelling units required to make up a suitable energy demand for a DEUS fuel cell power plant. Several types of mixed residential neighborhoods have been defined by Real Estate Research Corporation (1).

The two neighborhoods that were screened for DEUS application include a "planned mix" and a "high density planned neighborhood" as outlined in Table 4-2. Thermal loads were calculated for each of these neighborhoods and were subsequently used to estimate the relative sizes of each neighborhood that would be required to support the thermal output of a 1-5 MW fuel cell power plant. As the results in Table 4-2 indicate, the resulting sizes are not unusually large relative to typical suburban residential developments.

Commercial Applications. The types, qualities and uses of thermal energy for commercial applications are assumed to be the same as those identified for residential applications above. Obviously, the amounts that are demanded for each use will differ considerable. Three types of retail/services development were considered; convenience center, commercial strip and commercial center.

The general composition of each development is summarized in Table 4-3. Based on typical floor space allocations for the various tenant establishments, peak thermal loads for typical winter days were computed for each development type. The results of these calculations also are presented in Table 4-3.

It was concluded that commercial centers with greater than 286,000 square feet of floor space would require the thermal output from a fuel cell of 1 MW or greater.

Central Business District. Central Business Districts (CBD's) of cities throughout the United States could provide large thermal loads for DEUS fuel cell power plants. Thermal loads for these areas have somewhat different characteristics than those for the mixed retail developments considered above, because central business districts may include some different types of buildings (such as hotels, banks, and offices). Also, the average number of stories in buildings in

Table 4-2

ENERGY COMSUMPTION SUMMARY - MIXED RESIDENTIAL NEIGHBORHOOD

DATA ITEM	COMMUNITY DEVELOPMENT PATTERN	
	Planned Mix	High Density Planned
Neighborhood Composition by Dwelling Unit Type SFD- single family, detached SFA- single family, attached MFLR- multi-family, low rise MFHR- multi-family, high rise	40% - SFD 20% - SFA 20% - MFLR 20% - MFHR	10% - SFD 20% - SFA 30% - MFLR 40% - MFHR
Average Number of Persons per Unit	3.3	3.3
Dwelling Units (DU's) per Net Residential Acre	6.9	13.4
Peak Thermal Load per DU, 10^6 Btu/hr	24.8	19.6
Number of DU's Required for 1 MW_{th} Peak Load	138	174
Size of Residential Neighborhood, Acres for 1 MW_{th} Peak Load	20	13

Sources: <u>Residential and Commercial Energy Use Patterns</u>, 1970-1990, Arthur D. Little, Inc., 1974; <u>Analysis of Energy and Utility Service Demands, Vol. I</u>, Mathtech, 1977; <u>The Costs of Sprawl</u>, Real Estate Research Corp., 1974; modified by Mathtech.

Table 4-3
ANALYSIS OF TYPICAL COMMERCIAL DEVELOPMENT TYPES

Location	TYPE OF DEVELOPMENT		
(site in Northeastern U.S. assumed	Convenience Center (located in residential neighborhood)	Commercial Strip (adjacent to residential neighborhood)	Commercial Center (adjacent to residential neighborhood)
Typical Composition	o food stores o miscellaneous services	o one supermarket o one dept store o misc. retail/services	o one supermarket o two large dept. stores o misc. retail/svcs.
Building area, SF	7500	200,000	240,000
Land Area, SF	21,780	1,100,000	720,000
o Annual Consumption, 10^6 Btu/SF/YR	.0501	.0259	.0239
o Seasonal Load Factor	.42	.42	.42
o Typical Day in Peak Month			
o Daily Load Factor	.522	.522	.522
o Peak Load, 10^6 Btu/hr	.187	2.58	2.75
o Peak Thermal Needs in Megawatts	0.05	0.76	0.84

Sources: H. Fallah, R. Wakefield & D. Limaye, Comprehensive Community Planning for Energy Management and Conservation, Design of Community Energy Demand Generator, Report submitted by Mathtech, Inc. to Hittman Associates Inc., 1977;
J. Orlando, H. Fallah & D. Limaye, Analysis of Energy and Utility Service Demands, Draft Report submitted by Mathtech, Inc. to U.S. Department of Energy, 1978.

a CBD is likely to be greater than that for shopping centers. Most of this thermal energy would be used for space-conditioning and domestic hot water production, but it is conceivable that uses for commercial or industrial process heat could also be supplied. Table 4-4 shows the very large thermal loads estimated for a one square mile section in the downtown core of Baltimore, Maryland's central business district. As these figures indicate, even a small fraction of a city's CBD could present a potential thermal load for a DEUS fuel cell of 5 MW or larger. In addition, fuel cell power plants are particularly attractive for urban sites because of their extremely low environmental impact and aesthetic acceptability.

Mixed Residential/Commercial Applications. Given that commercial developments often are built adjacent to residential neighborhoods, it is necessary to examine the combined peak thermal energy requirements of residential and commercial developments. Six such developments were examined, including combinations of each commercial development type with either 50 dwelling units of single-family detached housing or 200 dwelling units of multi-family high rise housing. The specific mixes considered include:

- convenience center plus 50 dwelling units (DU's) of single-family detached (SFD) housing;
- convenience center plus 200 DU's of multi-family high rise (MFHR) housing:
- commercial strip (200 thousand sq. ft.) plus 50 DU's of SFD housing;
- commercial strip (200 thousand sq. ft.) plus 200 DU's of MFHR housing;
- commercial center (240 thousand sq. ft.) plus 50 DU's of SFD housing; and
- commercial center (240 thousand sq. ft.) plus 200 DU's of MFHR housing.

Load profiles were computed and analyzed, and as expected for both the residential/strip and residential/center development types, the resulting (combined) load profile is a better match with typical utility electric load profiles than is either of the component (residential or commercial, alone) profiles. The effect of combining such profiles may clearly be seen in Figure 4-2, which shows the individual and combined profiles for the residential/commercial mix. Residential/commercial mixes were selected for detailed analysis as potential DEUS applications.

Table 4-4

ENERGY CONSUMPTION SUMMARY TABLE FOR BALTIMORE, MD
CENTRAL BUSINESS DISTRICT

DATA ITEM	VALUE
Approximate size of sample area	1 sq. mi.
Approximate floor space by building type, sq. ft.	
• Offices	6,500,000
• Hotels/Motels	950,000
• Multi-family, Low Rise	1,000,000
• Multi-Family, Hi-Rise	350,000
• Misc. Stores & Services	1,710,000
• Warehouses	440,000
Total Annual Thermal Requirements, 10^9 Btu	1514
Average Annual Thermal Load 10^6 Btu/hr	173
Annual Peak Thermal Load, 10^6 Btu/hr.	493

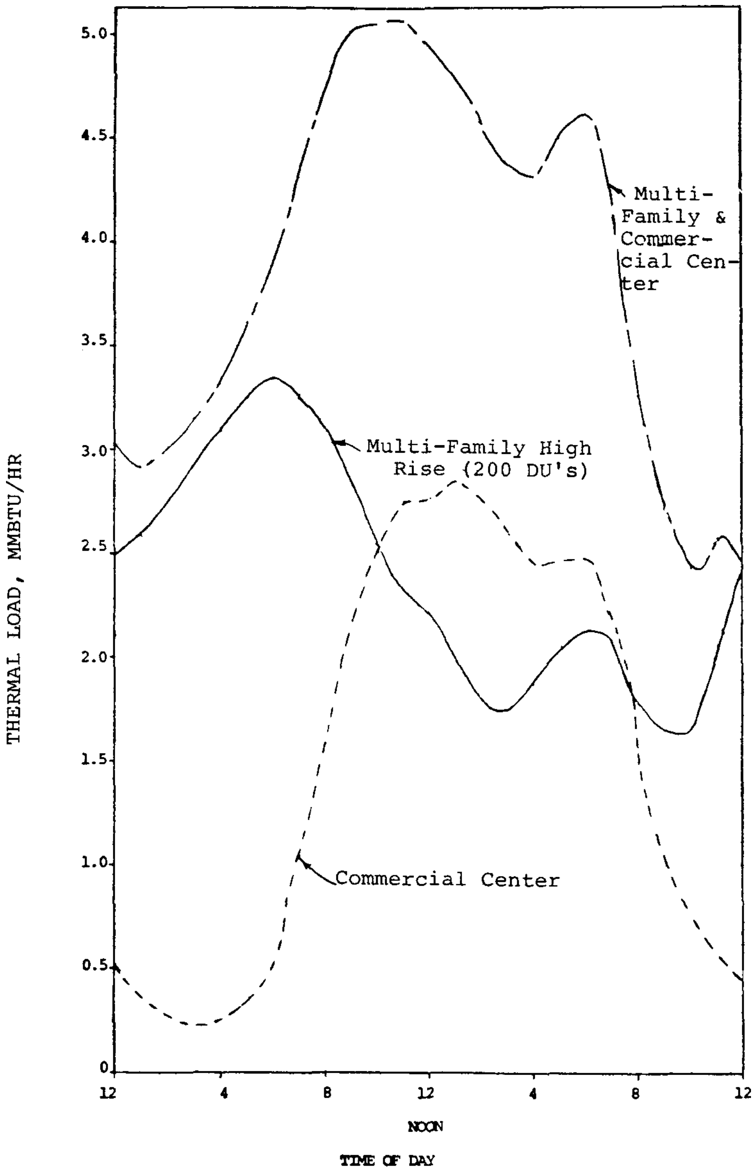

Figure 4-2. Winter Thermal Load Profiles for a Commercial Center/Residential Mixes
Source: Analysis of Energy and Utility Service Demands, Vol. 1, Mathtech, 1977; The Costs of Sprawl, Real Estate Research Corp., 1974; modified by Mathtech.

Office Buildings. Office buildings can use 180° to 210 $^{\circ}F$ thermal energy for hydronic space heating and cooling and $155^{\circ}F$ to $210^{\circ}F$ thermal energy to produce $140^{\circ}F$ domestic hot water. The thermal energy may be in the form of hot water or low-grade steam.

To establish a range of office building thermal loads, peak thermal loads were calculated for both a Northeastern site in winter and a Southern site in summer. Calculations for the Northeastern site indicated that approximately 63,000 square feet of office space would be needed to make up a peak thermal load equivalent to the output of a 1 MW fuel cell power plant. For the Southern site, on the other hand, the peak thermal load was considerably larger and only 36,000 square feet were required to produce a peak thermal requirement of 1MW. These results are summarized in Table 4-5.

Hospitals. Hospitals use large quantities of thermal energy for space heating, cooling, and water heating. Because hospitals require large air flows, it is difficult to make efficient use of the thermal energy radiated by electric lighting and people in the building. Instead, large quantities of outside air (usually 100% outside air) must be heated (or cooled), circulated and rejected. As a consequence of these special ventilating requirements, hospitals tend to have much higher energy consumption than those of other buildings (such as offices) of the same size. Hospitals also have a large requirement for hot water. A typical hospital in the Northeast required 6490 Btu/hr of hot water per bed.

While hospital energy consumption might be expected to vary considerably with geographic location, a geographic analysis indicated that hospital energy use is more dependent on other factors.

The results of calculations for the 755-bed University of Pennsylvania Hospital are presented in Table 4-6. As the table indicates, this hospital had a typical peak thermal requirement of 13.4 MW_{th} and would require a DEUS fuel cell plant with an electrical capacity of 11.1 MW_e. A hospital of at least 282 beds would be required to utilize the thermal output of a 5 MW_e fuel cell power plant.

Table 4-5

ENERGY CONSUMPTION SUMMARY TABLE FOR OFFICE BUILDINGS

DATA ITEM	VALUE	VALUE
• Geographic Location	South	Northeast
• Thermal Service Provided	Space Cooling	Space Heating
• Annual Thermal Energy Requirement* Btu/ft^2/yr	101,000	115,000
• Seasonal Load Factor	0.297	0.417
• Typical Day in Peak Month		
- Daily Load Factor	0.610	0.59
- Peak Load, Btu/ft^2/hr	64.6	52.2
- Peak Load for Space Conditioning and DHW Combined, Btu/ft^2/hr	94.3	54.4
- Office Space Required for a 1 MW$_{th}$ Peak Load, ft^2	36,000	62,700

* In arriving at this figure, it was assumed that absorption chillers with an average COP of 0.65 would be used in place of existing electric compression chillers with an average COP of 3.2.

Source: Mathtech estimates based on Energy Conservation In New Building Design: An Impact Assessment of ASHRAE Standard 90-75, A. D. Little, Conservation Paper No. 43B, 1976; Analysis of Energy and Utility Service Demands, Vol I, Mathtech, 1977

Table 4-6

ENERGY CONSUMPTION SUMMARY TABLE FOR TYPICAL HOSPITAL

DATA ITEM	VALUE
Specific Application	Univ. of Penn. Hospital (900,950 ft^2, 755 beds)
Thermal Service Provided	Space Conditioning and Domestic Hot Water
Annual Average Energy Consumption, Btu/ft^2 hr	27.4
Annual Average Load, 10^6 Btu/h	24.7
Seasonal Load Factor*	.72
Typical Weekday in Peak Month (January)	
- Daily Load Factor	0.75
- Peak Load, 10^6 Btu/hr	45.7 (13.4 MW$_{th}$)

* Seasonal load factor is defined as the ratio of annual average load to the average load for the peak month.

Source: <u>Energy Consumption at the Hospital of the University of Pennsylvania</u>, Energy Management Consultants, 1975.

Colleges and Universities. Colleges and universities were considered as potential DEUS applications because they represent a single large thermal load under single management. Distric heating systems are frequently found in university complexes.

The University of Florida (24,000 students) in Gainesville, Florida, was selected as a specific site for the analysis of university energy consumption. The results of this analysis are summarized in Table 4-7. Assuming a linear relation between size and thermal energy use, a university with approximately 3,430 students and 1,000,000 sq. ft. of floor space would require a DEUS fuel cell of approximately 5 MW capacity.

There are at least 100 colleges and universities of that size or larger in the United States. These results should be interpreted carefully, however, since a great variation in energy demands was found among institutions of similar size. This variation is due in part to the wide diversity in the mix of building types and usage patterns at such institutions.

Given the large size of the thermal load presented by universities, geographic location is not likely to have a large effect on the availability of applications for fuel cell power plants of 5 MW capacity and larger. An analysis of a university in a Northern climate confirmed this.

In general, colleges and universities appear to provide a number of excellent opportunities for utilizing DEUS plants. On campuses where a central power plant and/or a thermal energy distribution network already exists, the potential for such an application may even be greater.

Military Bases. Most military bases are composed largely of office buildings, barracks and other residential buildings. All of these buildings require space conditioning and domestic hot water. In addition, most bases have other large buildings that serve as warehouses, depots and hangars. Some of these buildings require large amounts of energy for space conditioning. It is assumed that the requirement for space conditioning could be met with thermal energy at temperatures of from 180°F to 200°F and that the requirements for domestic hot water could be met with 140°F water.

Table 4-7

ENERGY CONSUMPTION SUMMARY TABLE FOR THE UNIVERSITY OF FLORIDA

DATA ITEM	VALUE	
Specific Application	University of Florida (7,000,000 ft^2, 24,000 students)	
Thermal Service Provided	Space Conditioning and DHW	
Annual Average Load, 10^6 Btu/hr	117	
Seasonal Load Factor	0.90	
Peak Summer Day (August)	Using Steam-Driven Compression Chillers	Using Absorption Chillers
Average Load, 10^6 Btu/hr	130	351
Daily Load Factor	0.842	0.842
Peak Load, 10^6 Btu/hr	154 (45.1 MW_{th})	416 (122 MW_{th})

* A COP of 3.2 was assumed for the compression chillers; a COP of 0.65 for the absorption chillers.

Source: *Integrated Utility Systems Feasibility Study and Conceptual Design at the University of Florida*, prepared for HEW by Reynolds, Smith and Hills, Jacksonville, Florida, 1976.

The quantity of thermal energy that would be required to heat a typical military base is as difficult to define as what a "typical" facility might be. Thermal loads reported by Gamze-Korobkin-Caloger, Inc. (2) for a 1,200 man barracks complex at Ft. Belvoir, Virginia indicate that some military bases are large enough to require thermal energy at rates greater than 5 MW_{th}. This facility has a peak thermal load of 5.13 MW_{th} at a daily load factor of 0.901 on a typical winter day. Typical summer peak daily loads would be 3.66 MW_{th} at load factors at approximately 0.55.

Based on the Ft. Belvoir data, it would take at least a 1200-man barracks complex to make up a 5 MW peak thermal requirement in the Washington, D.C. area. Just how many U.S. bases have such facilities is not known. Some large bases undoubtedly would have a peak thermal demand many times higher than this.

Military bases are an application with significant potential for further investigation. While new bases are not being constructed, many existing bases will construct new barracks, officers'quarters, office buildings, warehouses, and depots. Further, as existing base power plants are scheduled for expansion or replacement, there will be a number of retrofit opportunities for DEUS fuel cell plants.

Table 4-8 summarizes the status of all the applications presented earlier (Table 4-1), including estimates of the number of application opportunities nationwide. As the table indicates, the most common reason for rejecting a specific type of building system was the lack of an adequate number of application opportunities. Primary and secondary schools, however, were eliminated because the quantity of thermal energy they typically require is too low to accommodate even a 1 MW fuel cell thermal output.

DEUS LOAD MATCHING/DECOUPLING OPTIONS

In this section, a number of options are presented for thermal and electric load matching. Each option is defined by the specification of both a plant design and an operating strategy. The first section discusses the major design considerations applied to DEUS fuel cell power plants and describes four design options used in the preliminary analysis of building system applications. The second section describes the generic strategies for operating DEUS plants and discusses their implications in terms of the four plant designs described previously.

Table 4-8

RESULTS OF BUILDING SYSTEM SCREENING PROCESS

	TYPE OF APPLICATION	COMMENTS
SELECTED	• High Density Residential and Residential Mixes	• Approx. 900 Units Required for 5 MW Plant
	• Commercial Mixes	
	- Regional Shopping Centers or Commercial Strip	• High Potential in Northern Regions; 1-5 MW Plant Required
	- Central Business District	• Dense Development; Applications Require Plant Size >5 MW
	• Commercial/Residential Mixes	• Attractive Load Profiles Possible
	• Office Buildings/Complex	• Single Building May Require 1-5 MW Plant; Complex Viable for Plant Size ≥5 MW
	• Hospitals	• Approx. 1400 Hospitals of Sufficient Size for Plant ≥5 MW
	• Colleges and Universities	• 100 Potential Sites for Plant Size ≥5 MW
	• Military Bases	• Plant Size 5 MW; Approx. 300 Existing Bases
REJECTED	• Low Density Residential	Approximately 100 Units Required for Plant Size >1 MW; however Thermal Distribution is Infeasible
	• Neighborhood Shopping Center	Thermal Requirements too low for even a 1 MW Plant
	• Primary and Secondary Schools	Thermal Requirements too low for Most Applications
	• Correctional Institutions	Poor Load Profile; Too Few Applications
	• Hotels/Motels	Fewer Than 100 Sites for Plant Size 1≥MW
	• Airports	Less than 30 Potential Sites
	• Wastewater Treatment	Fewer than 200 Sites for Plant Size 1≥MW

Finally, in the third section, a number of load matching options are synthesized by combining specific designs and operating strategies and the resulting options are prioritized for subsequent analysis.

DEUS Plant Design Alternatives. The single, most important DEUS plant design consideration is that of thermal supply sizing. One common aspect of all utility-owned cogeneration of DEUS plants is that they must provide the entire thermal supply for a given application, using combinations of on-site storage, boilers and fuel cells. The application's electrical needs, on the other hand, may be met from either the fuel cell or the utility grid.

The question that must be answered, of course, is how much and what type of thermal reserve capacity should be built into a DEUS plant to protect the thermal load. To a large degree, the answer to this question varies from application to application. Uninterrupted thermal supply to a hospital, for example, is considered more critical than continuous thermal service to a shopping center. If DEUS fuel cells constitute the only type of thermal capacity, it may be necessary to include one or more back-up boiler, storage or fuel cell units for contingencies. Such a possibility raises questions about the modularity of fuel cell power plants and the degree of interdependence among the modules. If other thermal "supplies", such as boilers or thermal storage are included in the DEUS fuel cell plant, they must be sized appropriately in relation to the fuel cell to assure adequate, but not excess, thermal capacity.

Four generic design alternatives that will be considered for each potential application are listed in Table 4-9. These include a DEUS plant that consists of:

- fuel cell alone,
- fuel cell/thermal storage combination,
- fuel cell/boiler combination, and
- fuel cell/thermal storage/boiler combination.

Each of these alternatives has a unique set of attributes and limitations that make it more or less attractive for specific DEUS applications. For example, in order to meet all peaks, a DEUS plant that supplies all of its thermal load from fuel cell cogeneration must be sized to meet thermal loads that are somewhat larger than the typical daily peak thermal loads. If this plant is operated only at those output levels required to meet the instantaneous thermal demand,

Table 4-9

DEUS PLANT THERMAL DESIGN ALTERNATIVES

Alternative	Comments
Fuel Cell Only	● For typical thermal load factors (50%-60%) capacity factors will be quite low
Fuel Cell with Thermal Energy Storage	● Makes use of thermal energy generated at a time when it is not needed; can serve as a thermal reserve or be used for thermal peaking/shaving
Fuel Cell with Supplemental Boiler	● Boiler used as a thermal reserve and for thermal peaking/shaving
Fuel Cell with Thermal Storage and Supplemental Boiler	● Provides maximum decoupling between fuel cell electrical and thermal outputs

it will generally have a low capacity factor for many building system applications. If, on the other hand, the plant is usually operated at full electrical capacity, it will generate an excess of thermal energy that cannot be used and will therefore be much less efficient. For applications with more predictable load profiles and high load factors, however, such a plant design may be adequate.

Generally, it will be necessary to include supplemental thermal capacity in the DEUS plant. Specifically, this analysis will consider the inclusion of either a boiler, thermal storage or both.

The advantages of a supplemental boiler are that it can supply the thermal load during scheduled or forced outages of the DEUS fuel cell and can at other times be operated in parallel with the fuel cell to meet thermal peaks. Thermal storage offers a somewhat different back-up capacity. If sufficient thermal energy is in storage during a period of high thermal demand, the requirement may be supplied from storage. In addition, in the design and evaluation process it is necessary to consider recharging storage on either a daily or weekly cycle.

One advantage of thermal storage is that it allows the DEUS plant to operate at higher electrical output levels than would be required to meet the instantaneous thermal load without wasting the thermal energy produced. Thus, the plant is freer to respond to the electrical demands of the utility system.

A combination of all three thermal supply options offers the greatest flexibility. Both the fuel cell and the boiler may be sized somewhat smaller than otherwise required, since thermal storage is available to help meet the unusually high thermal peaks. Further, the boiler provides an alternative means for charging thermal storage such as by use of off-peak electric power in a furnace, thus permitting an even greater amount of decoupling between thermal loads and the electrical demands of "the grid."

In the following sections strategies are described for operating a DEUS fuel cell plant: then the implications of applying these strategies to the plant designs of Table 4-9 are discussed.

Alternative Operating Strategies. The two primary operating strategies, economic and thermal dispatch, were described in Section 3. Under economic dispatch the fuel cell is operated only when scheduled to produce electricity by the owning utility. All thermal energy generated as a by-product of such operation would be available for use in meeting the site thermal needs. Any additional thermal energy required by the site would have to be met by a boiler or storage.* Under thermal dispatch, the fuel cell is loaded in such a way as to meet the thermal demands of the application, and the plant is given appropriate energy and capacity credits for electricity generated as a by-product of thermal production. If the application has a fairly constant thermal demand, day and night, the DEUS plant will displace (or delay the construction of) base-load coal and nuclear plants. If the application thermal load profile of the application is similar in shape to utility electric load profiles, then the thermal load-following DEUS plant might act more like peaking or intermediate load generation. The obvious advantages of this strategy are that it minimizes the requirement for supplemental thermal supply and that it maximizes the amount of cogenerated thermal energy.

Other strategies that combine aspects of both economic and thermal dispatch also are possible, such as economic dispatch during the on-peak hours and thermal dispatch off-peak. Some of these alternatives are explored in the analyses described below for specific designs and applications.

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* For some applications it might be reasonable to consider not meeting or only partially meeting some small portion of the customer's typical thermal load. In the case of some building systems, space conditioning may be cut back to a low, but adequate, maintenance level. In some cases, this load may be unnecessary; in others, the customer may be able to satisfy his "off-hour" loads by a much simpler and less expensive alternative system. Unless otherwise stated, however, it is assumed that the DEUS plant must satisfy all thermal loads.

Load Matching/Decoupling Options. Combining each of the four design alternatives presented above with each of the primary operating strategies, a matrix of options for thermal/electric load decoupling can be constructed. Such a matrix is presented in Table 4-10. Most of the options are obvious. However, two have only limited applications when considered in the context of typical building system thermal load profiles. Specifically, the first option listed under "Economic Dispatch" would be applicable only to applications with very low thermal loads during electric utility off-peak hours. The design for this option includes only a fuel cell as a thermal supply. Thus, no thermal energy or only a small amount could be supplied during the utility's off-peak hours. Because such an option is unattractive for the building system applications considered here, it was not analyzed further.

If it is assumed that given a choice the utility will favor operating the fuel cell according to economic dispatch, then it is probably not necessary to consider the option that combines thermal dispatch operation with a fuel cell, thermal storage, and a boiler. The reason is that such a plant design offers almost complete flexibility in specifying plant electrical generation. Thus, if the utility chooses to operate the fuel cell according to electric dispatch guidelines, this option will be the same as the economic dispatch case with a similar plant design. Therefore, this option was not considered further.

APPLICATIONS ANALYSIS

In analyzing the various DEUS options presented above for building systems, a methodology which combines manual and automated computation was utilized. As Figure 4-3 shows, the sizing of the fuel cell and preparation of fuel cell and boiler operating schedules then become inputs to the economic and energy supply impact evaluations. In this section the three components of the building system analysis are described separately, including a discussion of all major inputs, outputs and assumptions.

Table 4-10

OPTIONS FOR THERMAL/ELECTRICAL LOAD MATCHING OR DECOUPLING

DEUS DESIGN ALTERNATIVE	OPERATING STRATEGY	
	ECONOMIC DISPATCH	THERMAL DISPATCH
Fuel Cell Only	DEUS operates only as dispatched by the utility (generally only during on-peak hours); no thermal backup; this option was not analyzed.	* Electricity strictly a byproduct; some fuel cell redundancy required as backup
Fuel Cell and Thermal Storage	Thermal storage available for low level thermal maintenance during off-peak hours; limited applications	Storage used to meet thermal peak loads; some redundancy required for back-up
Fuel Cell and Supplemental Boiler	*Boiler available as back-up and during off-peak hours	Boiler used as thermal supply back-up and to meet peak loads
Fuel Cell with Storage	Boiler and storage may be sized to make maximum use of fuel cell thermal energy	Careful selection of boiler and storage will permit almost any fuel cell operating schedule; this option was not analyzed.

* Designates baseline option

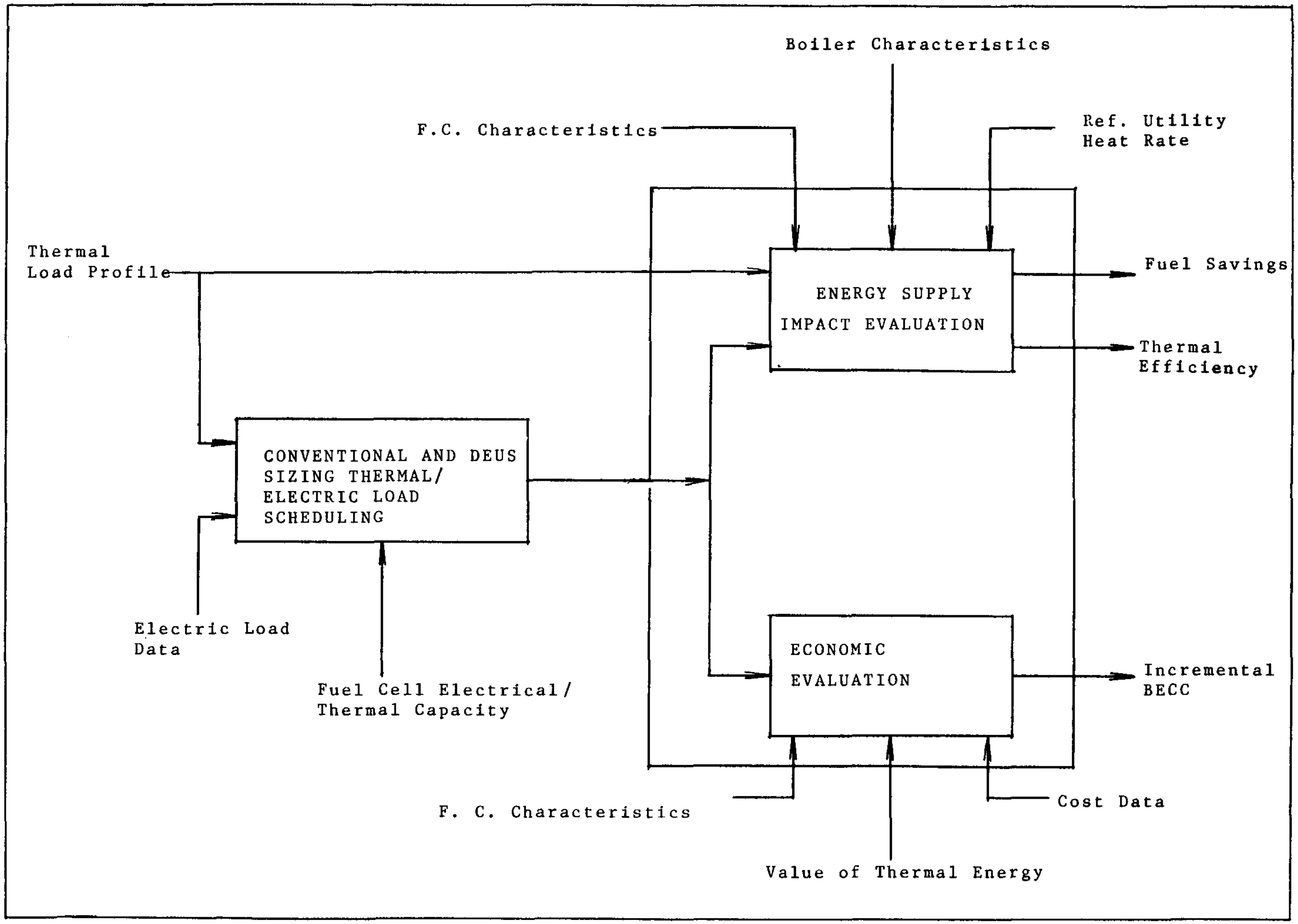

Figure 4-3. Framework for Building System Analysis.

DEUS Sizing and Load Scheduling

The guidelines used in fuel cell and boiler sizing and in specifying plant operating schedules are outlined in Table 4-11. A major assumption in sizing the plant was that the total fuel cell capacity for each application would be composed of discrete numbers of 4.5 MW, building blocks. This assumption was based on

- the ready availability of performance and cost data for United Technologies Corporation's 4.5 MW Demonstrator fuel cell;
- a desire that the evaluations and comparisons of different size fuel cells be made on as consistent a basis as possible.

In most cases where the assumption of 4.5 MW modules precluded sizing the fuel cell to the most desirable capacity for a given application, it was possible to "match" the fuel cell to the load using one of the options described in the previous section. In the few cases where this was not possible, the loads were scaled up or down to achieve a better match. Within the bounds of this constraint fuel cells were sized as closely as possible to

- the peak thermal load for options that included a fuel cell only
- the average thermal load for options that included a boiler without thermal storage
- a level high enough to provide adequate energy to storage on the day of peak thermal demand for options that included thermal storage

Supplemental boilers were sized to provide a 33% margin above the anticipated peak boiler load.* Thermal storage was sized only to meet the anticipated requirement; no reserve margin was included.

Once equipment sizing was determined, operating schedules were prepared for each of several typical daily load profiles. For most of the applications hourly schedules were prepared for typical days in each of the four seasons. Each of the load schedules was then weighted according to the number of days it represented and used to calculate annual economics and energy use. Because of a lack of data, however, the central business district application had to be evaluated based on only two profiles. In these instances, of course, higher weightings were assigned to each profile.

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* It was assumed that two boilers, each sized at approximately two thirds of the peak thermal load, would be required to provide an adequate auxiliary source of thermal energy.

Table 4-11

GUIDELINES FOR PLANT SIZING AND SCHEDULING

Design Alternative	Operating Strategy	
	Economic Dispatch	Thermal Dispatch
Fuel Cell Only	(not analyzed)	Size fuel cell to meet peak demand; follow thermal load.
Fuel Cell with Boiler	Size fuel cell to average thermal load on peak day; size and operate boiler to meet excess and off-peak thermal demand.	Size fuel cell to meet average thermal demand on peak day; size boiler to meet excess. Operate fuel cell at either economic or thermal dispatch level (whichever is lower).
Fuel Cell with Thermal Storage	Size fuel cell to supply enough thermal storage to meet all off-peak thermal demand on peak day; size storage accordingly.	Size fuel cell and storage to meet total thermal demand on peak day. For all other days utilize storage to keep fuel cell operating level as close to economic dispatch as possible.
Fuel Cell with Boiler and Storage	Size fuel cell to supply enough thermal storage to meet off-peak thermal demand on average day; size boiler to meet any excess demand.	(not analyzed)

Determinations of operating schedules that were optimum either with respect to annual costs or energy use was beyond the scope of this effort. Instead, general guidelines were established to define the ways in which the various equipment items would be used, and scheduling was handled on a case-by-case basis. For the options that include economic dispatch the guideline was that both the boiler and thermal storage would be used so as to reduce the required fuel cell capacity and at the same time ensure fuller utilization of fuel cell thermal energy. For the options that included thermal dispatch, on the other hand, the guideline was to employ the boiler and/or thermal storage in a way that would allow the fuel cell to operate as close as possible to economic dispatch. The rationale for this guideline is that economic dispatch represents the "ideal" fuel cell operating strategy from the utility point of view. Therefore, whenever DEUS plant design options can be utilized to "decouple" fuel cell operation from the thermal requirements of a specific application, the objective should be to give the utility greater control over fuel cell electrical generation. Specific examples of the resulting fuel cell, boiler and thermal storage operating schedules are provided later in the discussion of analysis results.

Once specified, plant operating schedules are combined with various other data, to calculate annual energy supply and economic performance measures based on the equations presented in Section 3. The inputs, outputs, and general flow of these calculations are described below.

Economic Evaluation

The equations used in calculating the incremental breakeven capital cost of a fuel cell DEUS were presented in Section 3. As Figure 4-4 shows, the evaluation simply combines the thermal and electric load profiles, the fuel cell characteristics, and various economic data to calculate the required inputs for these calculations. Both incremental production costs and incremental credits are calculated.

Incremental Production Costs. In analyzing incremental production costs total annual production costs for both the DEUS plant and the conventional fuel cell plant are calculated and the difference is determined. As Figure 4-4 shows, operation and maintenance costs and fuel costs must be calculated for each plant type. For the conventional fuel cell plant O&M costs are calculated simply by

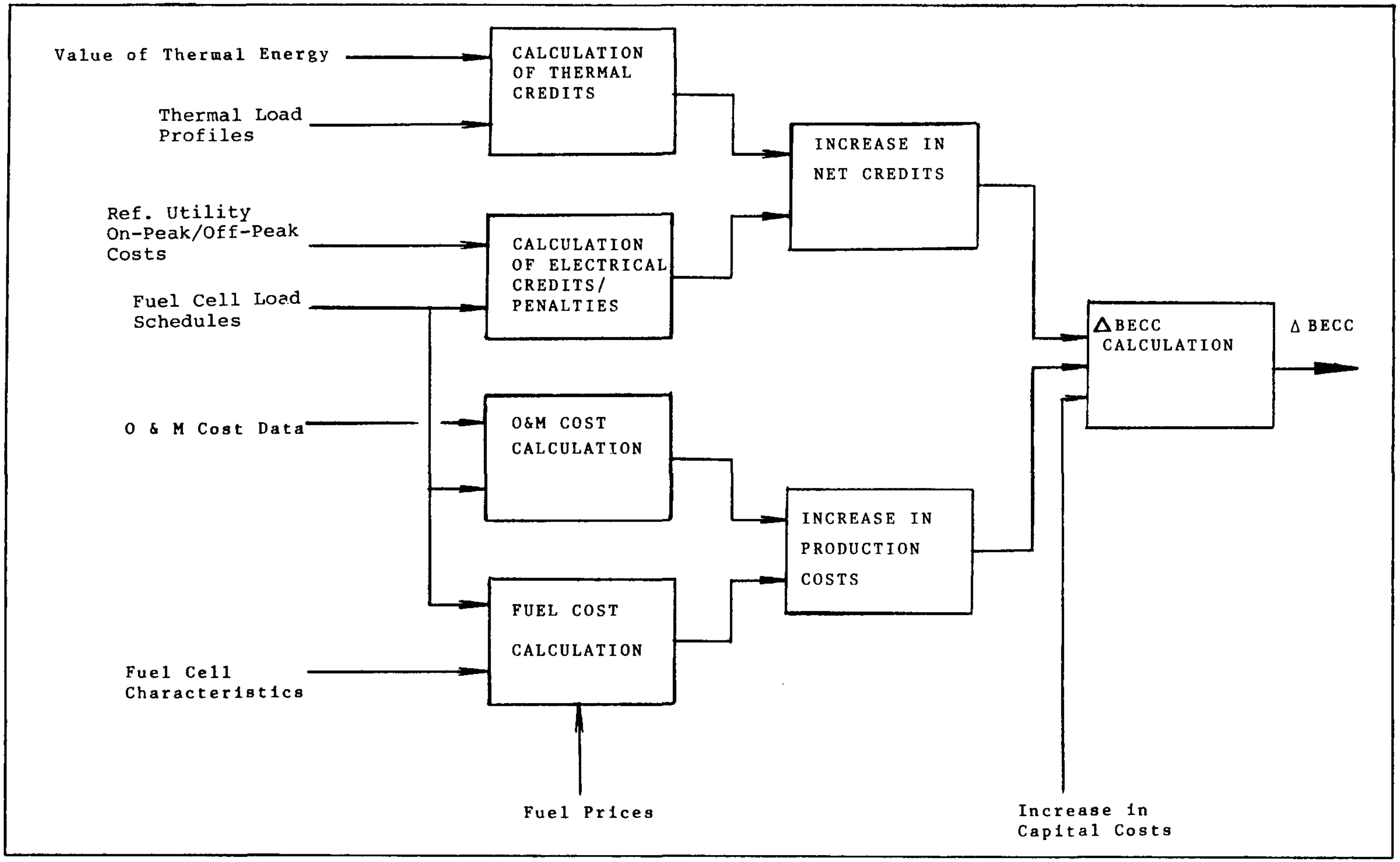


Figure 4-4. Framework for Economic Analysis

summing the total annual electrical production of the fuel cell and multiplying by assumed O&M cost constant of 2.85 mills/kWh. For the DEUS plant, boiler, storage,or distribution system O&M costs may also be required. Boiler and thermal distribution system O&M costs were assumed to be 2.5 percent and 3 percent of installed capital cost, respectively. Thermal storage O&M costs were not known and were assumed to be within the error of estimation of total storage capital costs. For DEUS options that operated on economic dispatch, the only difference between DEUS and conventional fuel cell O&M costs was the added O&M costs for these plant auxiliaries (boiler and thermal distribution system). For options that operated according to thermal dispatch, on the other hand, the electrical productions of the DEUS and conventional fuel cells typically were different, and fuel cell O&M costs also differed.

In calculating fuel costs, it was necessary to determine the heat rate corresponding to each hourly fuel cell operating level and multiply by the energy produced and the price of fuel. These hourly costs were then summed over the entire year to obtain annual fuel costs for the fuel cell. Boiler fuel costs for the DEUS plant were calculated simply by dividing the total boiler thermal output by 0.83, the assumed average boiler efficiency.

Incremental Net Credits. Incremental thermal and electric credits (debits) to the DEUS plant are calculated as described in Section 3. These are then summed in arriving at "net credits". Thermal credits are determined by calculating the total annual thermal production and multiplying by the assumed value of thermal energy. For the building system analyses thermal energy (210^{o}F hot water) was assigned a very conservative value equal to the approximate fuel cost of producing an equal amount of heat with a boiler or hot water generator. For the baseline fuel cost of $\$2.45/10^{6}$ Btu, the value of thermal energy was $\$3.00/10^{6}$ Btu.

On-peak and off-peak (penalty costs) are calculated as described in Section 3 whenever there is a difference between the hourly electrical productions of the DEUS and conventional plants. As described earlier, these are based on the average on-peak and off-peak incremental energy costs of the reference utility. The values used were

• Average On-Peak Energy Cost	30.4 mills/kWh
• Average Off-Peak Energy Cost	21.3 mills/kWh

Energy Supply Impact Evaluation

All energy supply comparisons are based on an assumed parity in electrical and thermal production by the DEUS plant and the conventional alternative. For the conventional system thermal energy is assumed to be produced by a boiler with an efficiency of approximately 83 percent. In those cases where the electrical production of the DEUS plant exceeds that of the conventional fuel cell, the conventional system is charged with the fuel required to produce the deficit at the reference utility system heat rate. On the other hand, when the electrical production of the conventional fuel cell exceeds that of the DEUS plant, the DEUS incurs a similar charge. Figure 4-5 illustrates the flow of these calculations. As the figure shows, both on-peak and off-peak electrical production are calculated for each system. Using this information it is possible to determine the types of utility generation displaced (or required) by DEUS deviations from economic dispatch operation.

DISCUSSION OF RESULTS

As indicated previously, a large number of analyses were performed for different applications, plant designs, and operating strategies. A complete presentation of these results, including all load profiles, operating schedules, and input data would be overwhelming and confusing. Instead, this section provides a concise summary of the most interesting and pertinent results including

- detailed discussion of the analysis and results for one promising building system application - a hospital
- a comparison and discussion of economic and energy supply results for the baseline economic and thermal dispatch options for all applications
- an overview and summary of the results for all other load matching/decoupling options
- reports on the effects of alternative operating strategies and input data assumptions.

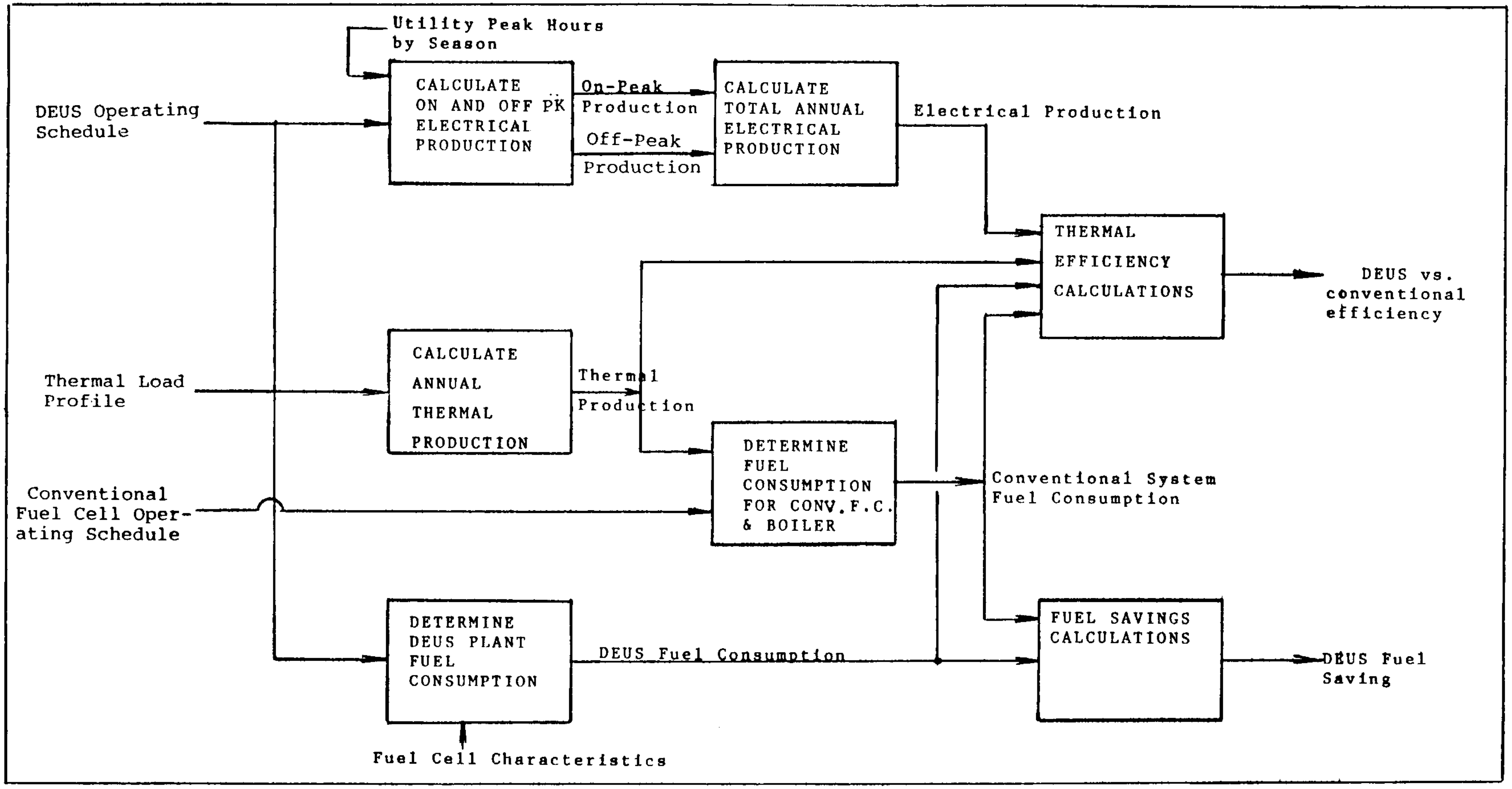


Figure 4-5. Framework for Energy Supply Impact Analysis.

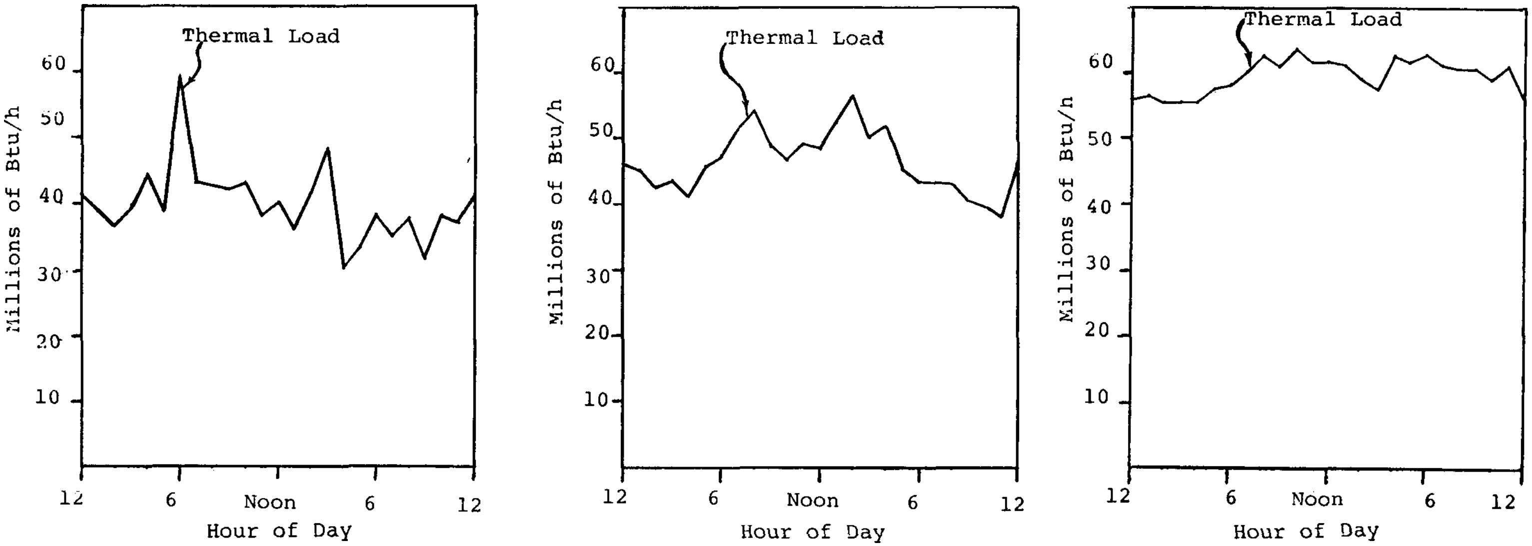
Illustrative Results for a Hospital

As a specific example of the type of analysis that was performed for each application, an in-depth description of the inputs and important outputs for a hospital application are presented. Energy loads for the hypothetical hospital that was analyzed were based on calculated data for the one million square feet Charity Hospital in New Orleans, Louisiana. The thermal load profiles shown in Figure 4-6 were calculated for this hospital, based on hourly energy demands reported in an Integrated Community Energy System Case Study of New Orleans, La., for the Department of Energy (3). In deriving these loads, it was assumed that 210°F hot water from a fuel cell DEUS would be used to meet all the space heating, space cooling, and hot water heating requirements of this hospital year round. Absorption chillers with an approximate COP of 0.60 were assumed in calculating the thermal loads for space cooling.

Various DEUS design alternatives were considered for this and other applications, as described earlier in this section. Figure 4-7 shows a conceptual schematic of these design alternatives for the hospital application.

Before the actual analysis could be performed, it was necessary to prepare operating schedules, specifying the hourly operation of the DEUS fuel cell and its auxiliaries for typical seasonal days. Figures 4-8 and 4-9 show the actual operating schedules for a typical summer day for all six of the options analyzed. Several of these schedules require comment. For example, for the economic dispatch option that includes thermal storage it was necessary to specify a fuel cell size that was considerably higher than that required to meet the peak thermal load in order to provide adequate thermal storage for off-peak consumption. During the spring and fall months, however, much of this additional thermal energy could not be used and was rejected. For the option that included both a boiler and a storage, a better "fit" was possible by the use of a smaller fuel cell, less thermal storage, and a small 32 million Btu/hr package boiler.

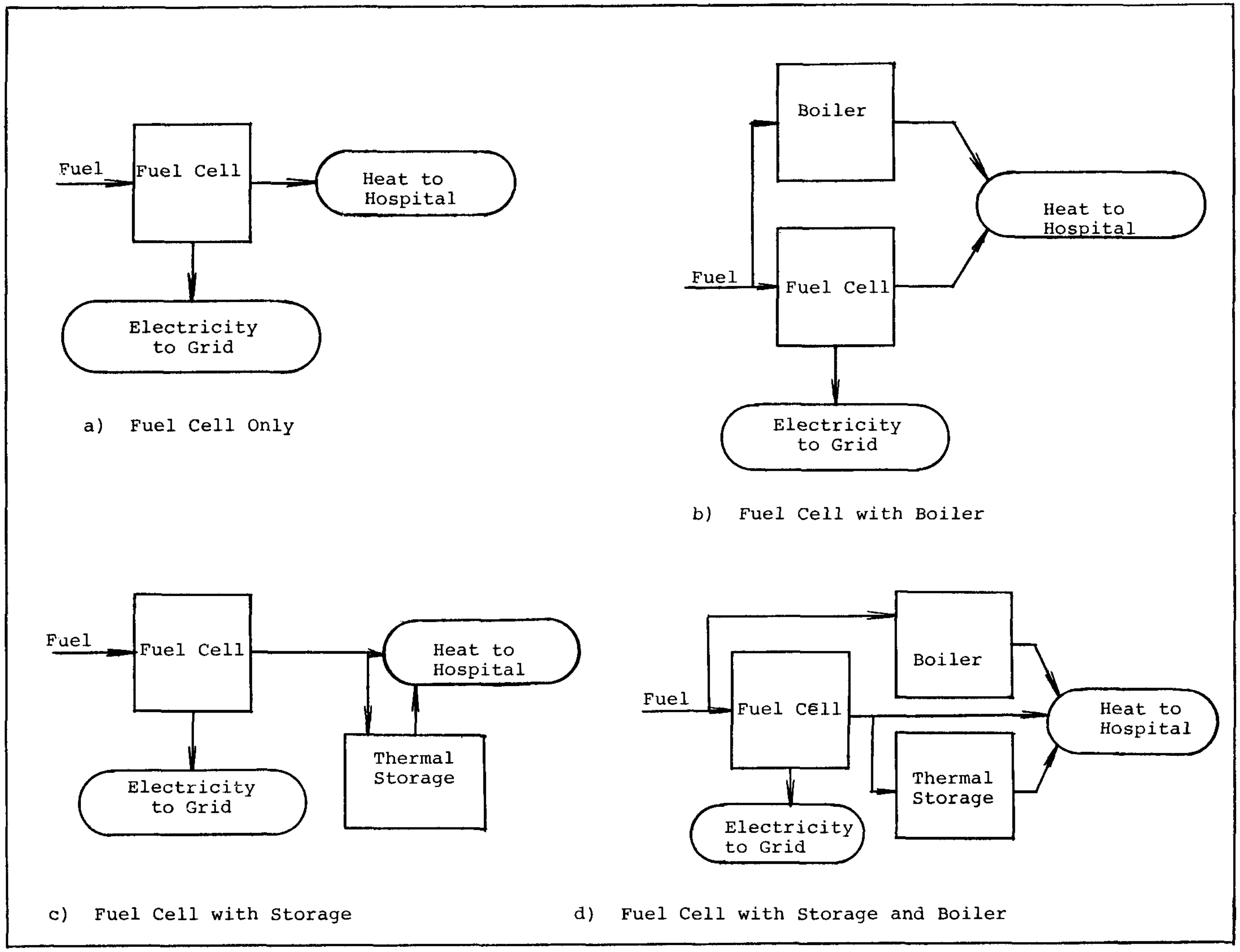
Two of the operating schedules shown in Figure 4-9 for thermal dispatch options also deserve comment. For the option that includes thermal storage, for example, the fuel cell was sized as closely as possible



a) Typical winter day b) Typical spring/fall day c) Typical summer day

Figure 4-6. Thermal Load Profiles for Charity Hospital, New Orleans, Louisiana

Source: Health Education Authority of Louisiana, et al., Grid Connected ICES Preliminary Feasibility Analysis & Evaluation, Final Report to ERDA, 1977.



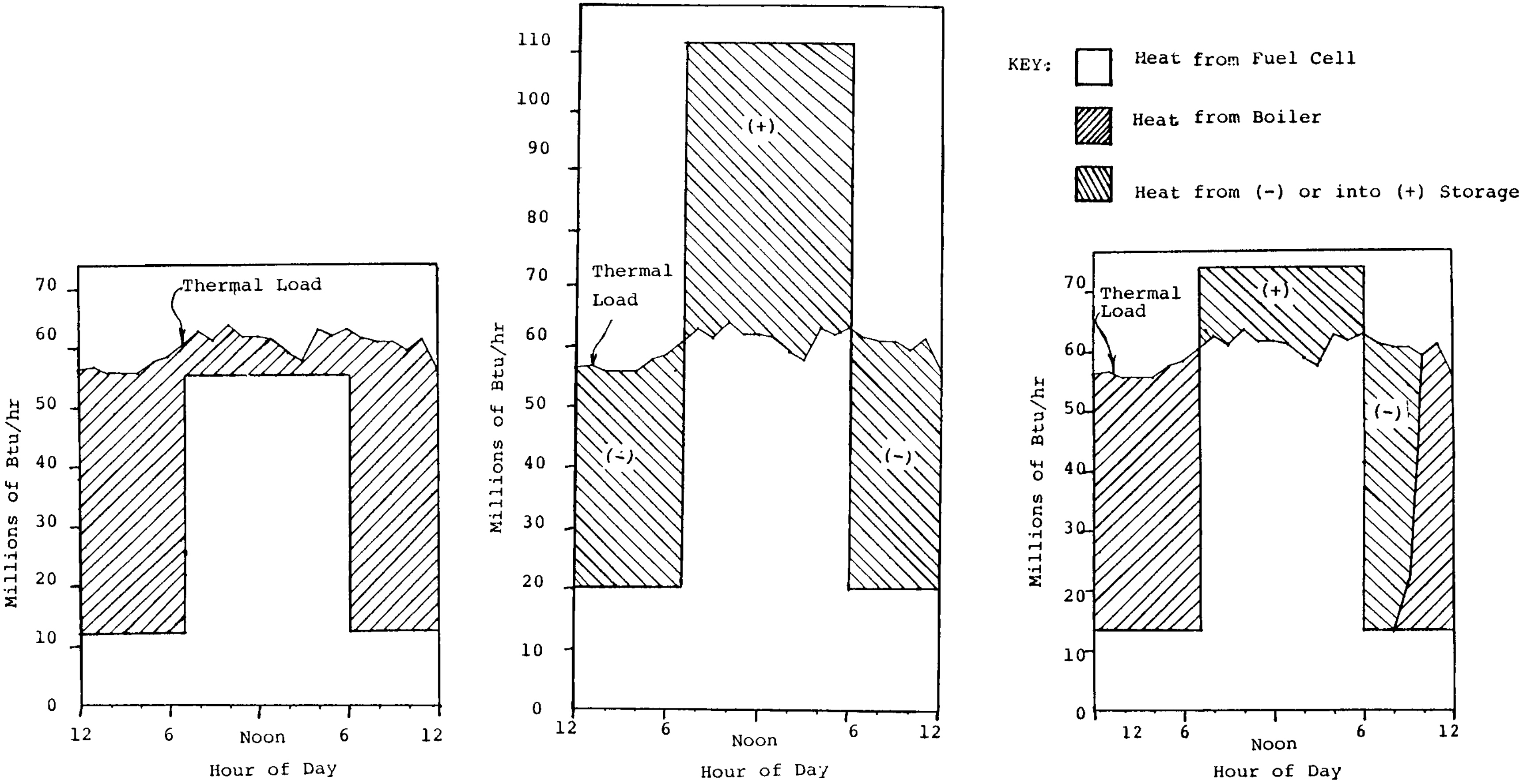
a) Fuel Cell Only

b) Fuel Cell with Boiler

c) Fuel Cell with Storage

d) Fuel Cell with Storage and Boiler

Figure 4-7. DEUS design alternatives for hospital.



a) Fuel Cell with Boiler

b) Fuel Cell with Storage

c) Fuel Cell with Boiler and Storage

Figure 4.8. DEUS Economic Dispatch Operating Schedules for a Hospital. (Typical Summer Day)

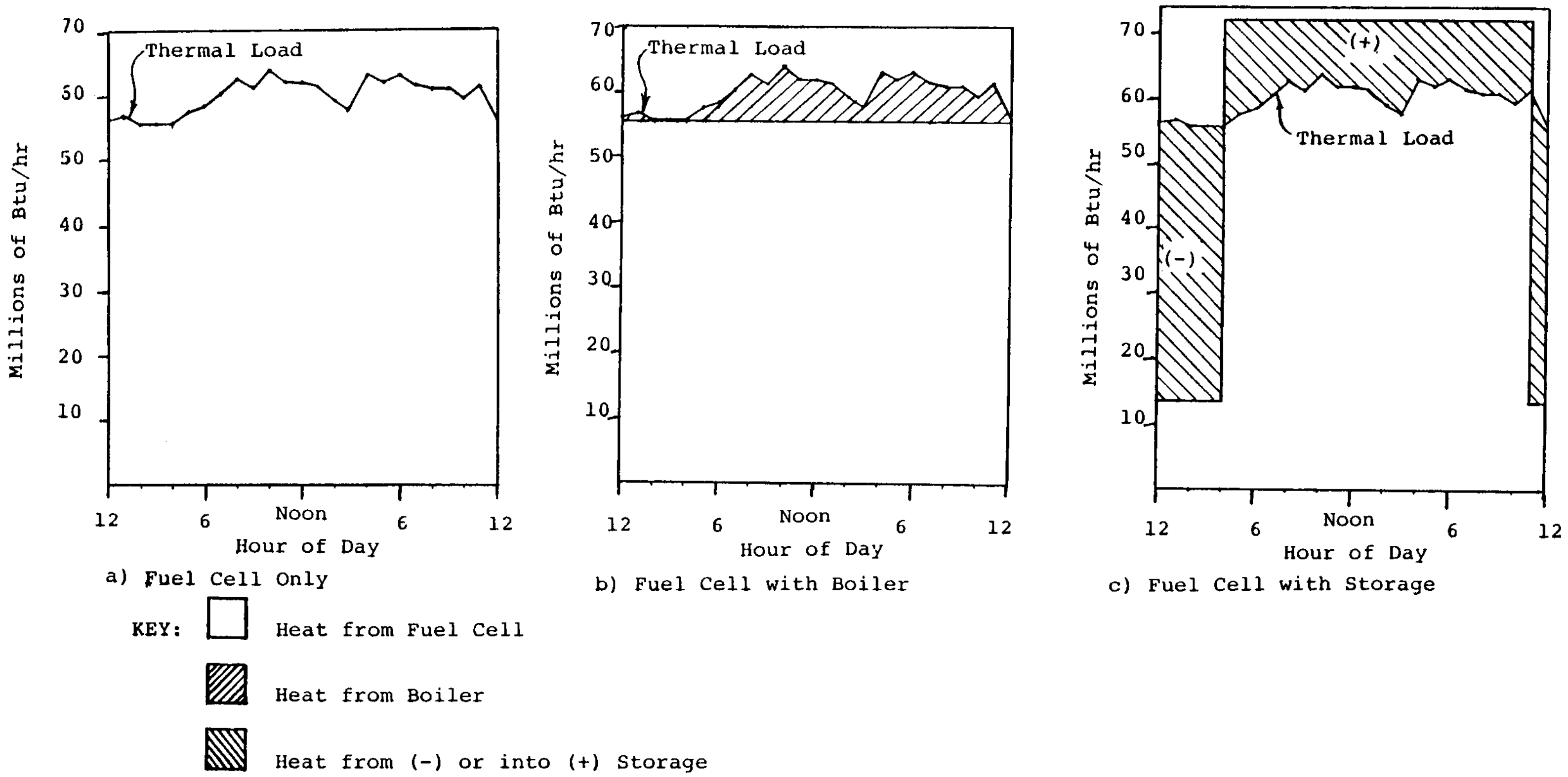


Figure 4-9. DEUS Thermal Dispatch Operating Schedules for a Hospital. (Typical Summer Day)

to the peak thermal load (which occurs in summer for the hospital). The fuel cell was then operated at its maximum load for an operating period that was extended as necessary to provide the thermal energy to storage required for off-peak consumption. During other seasons it was possible to make this operating period coincide exactly with the utility's on-peak hours and to reduce the fuel cell operating level as well. In accordance with thermal dispatch the fuel cell was never operating at any higher level than required to exactly satisfy the total thermal load. For the thermal dispatch option that includes a boiler, it was possible to size the fuel cell to the average rather than peak thermal load and achieve a higher annual capacity factor for the fuel cell.

Table 4-12 presents the important economic results for the options analyzed. These results clearly indicate that the hypothetical hospital analyzed is an attractive application for a fuel cell DEUS. In fact, the average value of ΔBECC for the options analyzed is of the same order as anticipated breakeven costs for the Type I fuel cell itself.

Several other observations also may be made. First of all, the Configuration A heat recovery costs are negligible relative to the breakeven costs that result for a hospital. Second, the values of ΔBECC for thermal dispatch operation are approximately 50 percent higher than those for economic dispatch. Thus, from an economic standpoint, it appears that the benefits of thermal dispatch operation (for a hospital) are greater than the penalty costs incurred. Finally, the results indicate that careful selection of auxiliary equipment can make a significant difference in DEUS economics. Increases in ΔBECC of from 10 to 25 percent are possible simply by adding a boiler or a boiler/storage combination.

The hospital energy supply results are summarized in Table 4-13. The efficiencies and fuel savings presented are based on Equations 3-8 through 3-12, as defined previously in Section 3. In general, DEUS efficiencies are near 80 percent and conventional system efficiencies are around 55 percent. As might be expected, DEUS efficiencies are a little higher for thermal dispatch, because thermal energy is produced only as it is required by the application. Conventional system efficiencies for thermal dispatch, on the other hand, are slightly

Table 4-12

SUMMARY OF ECONOMIC ANALYSIS RESULTS FOR A LARGE HOSPITAL

Economic Variable	Economic Dispatch			Thermal Dispatch		
	FC w/BLR	FC w/STOR	FC w/BLR & STOR	FC ONLY	FC w/BLR	FC w/STOR
Annual Thermal Credits, T_{er} (10^3 \$)	1272	1272	1272	1272	1272	1272
Annual Production Cost Increase, ΔP (10^3 \$)	512.9	0	165.7	0	41.1	0
Annual Penalty Costs, ρ (10^3 \$)	0	0	0	208.2	136.9	59.1
Plant Level Incremental Breakeven Cost (\$/kw)	298	249	325	312	429	356
Capital Cost of Auxiliaries (\$/kw)	78	38	76	0	30	35
ΔBECC (\$/kw)	220	211	249	312	399	321
Cost of Heat Recovery Modifications (\$/kw)	3	3	3	3	3	3
Net Credit to Fuel Cell (\$/kw)	217	208	246	309	396	318

Table 4-13

SUMMARY OF ENERGY SUPPLY RESULTS FOR A LARGE HOSPITAL

Annual Energy Supply Data Item	Economic Dispatch						Thermal Dispatch					
	Fuel Cell w/ Boiler		Fuel Cell w/ Storage		Fuel Cell w/ Boiler & Storage		Fuel Cell Only		Fuel Cell w/ Boiler		Fuel Cell w/ Storage	
	DEUS	CONV	DEUS	CONV	DEUS	CONV	DEUS	CONV	DEUS	CONV	DEUS	CONV
<u>Electrical Energy Supplied</u> (10^6 Kwh)												
● On-Peak	60.3	60.3	121	121	80.4	80.4	58.2	80.4	54.3	60.3	76.5	80.4
● Off-Peak	14.5	14.5	29	29	19.3	19.3	53.2	19.3	50.3	14.5	32.6	19.3
● Total	74.8	74.8	150	150	99.7	99.7	111.4	99.7	105	74.8	109	99.7
<u>Fuel Consumption</u> (10^4 Btu)												
● Fuel Cell	672	672	1344	1344	896	896	987	896	929	672	975	896
● Boiler	199				60				13			
● Total	871	672	1344	1344	956	896	987	896	942	672	975	896
Energy Utilization Efficiency	0.78	0.57	0.70	0.59	0.80	0.54	0.82	0.52	0.83	0.51	0.82	0.53
Thermal Energy Supplied (10^9 Btu)	424		424		424		424		4.24		4.24	
Fuel Savings Due to DEUS Operation (10^9 Btu)	312		253		451		555		583		538	

lower, because a certain amount of "deficit" electricity is assumed to be supplied at average utility system heat rates, as discussed in Section 3.

The load matching/decoupling option that includes thermal storage and economic dispatch results in high fuel consumption and relatively low efficiencies. This results from the need to size the fuel cell large enough to meet off-peak storage requirements on the day of maximum thermal demand and then to operate according to economic dispatch year-round. During the spring and fall, for example, thermal loads are relatively low, but the fuel cell must still operate at rated load during the on-peak period.

It may be observed that the amount of fuel saved due to DEUS operation is often higher than the amount of thermal energy supplied by the DEUS plant. For the economic dispatch option that includes both a boiler and storage, for example, 451 billion Btu's are saved annually, while only 424 billion Btu's are supplied to the hospital. In this instance, the larger savings are due to the assumption that the conventional system will supply the same amount of thermal energy using a conventional boiler at an efficiency of 83 percent. Thus, the maximum possible fuel savings for this option would be

$$424\text{x}10^{9} \text{ Btu}/0.83 = 511\text{x}10^{9} \text{ Btu} \qquad (4\text{-}1)$$

The large DEUS fuel savings for thermal dispatch are due in part to this same characteristic of the conventional system. However, the savings for thermal dispatch operation are even higher due to the assumption that differences between DEUS fuel cell and conventional fuel cell electrical production are equalized using electricity from the "grid", generated at the average system heat rate, which is considerably higher than typical fuel cell heat rates.

Although the thermal dispatch fuel savings presented in Table 4-13 appear attractive, they require careful interpretation. As the table indicates, the thermally-dispatched DEUS fuel cell produces less electricity during on-peak hours. Thus, the utility must operate an increased number of high-cost, peaking units during its on-peak hours and decrease production from low-cost base load units during off-peak hours. Since the baseload units typically do not use premium fuels, however, this thermally-dispatched, fuel cell DEUS may be saving abundant energy resources at the expense of scarce resources.

Baseline Results for all Applications

The "baseline" economic and thermal dispatch options are

- economic dispatch for a fuel cell with a supplemental boiler to supply off-peak thermal requirements
- thermal load following for a DEUS fuel cell only

The economic and energy supply results of analyzing these two options for Type I - phosphoric acid DEUS fuel cells are presented below for all applications. Before these results are presented, however, prototype applications are defined, and the baseline input data is summarized.

Type II fuel cells were not analyzed for building system applications, since their higher quality heat is not required for space conditioning or domestic hot water production. In addition, Type II fuel cells would provide somewhat less usable thermal energy per unit of electrical energy produced.

Prototype Applications. For each of the potential applications discussed previously, a prototype building (or building site) was selected to serve as a data source for detailed analysis. Where possible, data for actual buildings was used. In other cases, it was necessary to use hypothetical data from other studies. Table 4-14 describes the sizes and locations of these prototype applications and identifies the basic data sources. Thermal load profiles for these applications are presented in Appendix A.

Baseline Input Data. Table 4-15 summarizes the major input data assumed for the baseline analyses. Included are

- fuel cell and boiler sizes
- equipment capital costs
- assumed operating and maintenance costs
- various other data including the price of fuel and the value of thermal energy.

Table 4-14

DESCRIPTION OF PROTOTYPE APPLICATIONS

Prototype Application	Specific Site or Data Source	Size	Location
Hospital	Charity Hospital; ICES Case Study (3)	1 million sq. ft.	New Orleans Louisiana
Residential	Modular Integrated Utility System Demonstration Site HUD (4)	416 dwelling units, multi-family low and high rise	St. Charles, Maryland
Shopping Center	MIUS Conceptual Community NASA (5)	2 million sq. ft.	Washington, D.C.
Office Building	Ohio Legal Aids Building; Sepsy (6)	data scaled to 300 thousand sq. ft.	Columbus, Ohio
University	University of Florida, Reynolds, Smith & Hill (7)	24 thousand students, 7 million sq. ft.	Gainesville, Florida
Military Base	Ft. Belvoir Army Base; GKC (2)	1200 man barracks complex (scaled to 1900 man complex)	Ft. Belvior Virginia
Residential/ Commercial	Combination of Above Residential Site with One-Half of Above Shopping Center	416 multi-family dwelling units plus 1 million sq. ft. Shopping ctr/	Washington, D.C.
Central Business District (CBD)	Baltimore, Maryland CBD; Hittman Associates (8)	1 sq. mi. of downtown development	Baltimore, Maryland

Table 4-15

SUMMARY OF INPUT DATA FOR BASELINE APPLICATIONS

Application	Economic Dispatch				Thermal Dispatch			
	Fuel Cell Size (MW)	Auxiliaries	Auxiliary Costs		Fuel Cell Size (MW)	Auxiliaries	Auxiliary Costs	
			Capital($/kW)	O&M($/y)			Capital($/kW)	O&M($/y)
Hospital	13.5	Boiler (90 million Btu/hr)	77.8	26,250	18.0	None	-	-
Residential	4.5	Boiler (18 million Btu/hr) Thermal Distribution System	90.7	11,530	4.5	Thermal Distribution System	50.1	7980
Shopping Center	4.5	Boiler (42 million Btu/hr)	108	12,100	9.0	None	-	-
Office Building	4.5	Boiler (20 million Btu/hr)	33.8	3800	4.5	None	-	-
University	31.5	Boiler (190 million Btu/hr)	74.6	58,800	63.0	None	-	-
Military Base	4.5	Boiler (24 million Btu/hr)	37.8	4250	4.5	None	-	-
Residential/ Commercial	4.5	Boiler (38 million Btu/hr)	95.6	10,800	9.0	None	-	-
Central Business District	58.5	Boiler (450 million Btu/hr) Thermal Distribution System	596	870,000	121.5	Thermal Distribution System	227	828,000

Sources: Boiler Costs: personal communication, Burns and Row, Inc; and Gamze-Korobkin-Caloger, Inc; E. Farahan <u>Central Heating-Package Boilers</u>, prepared for Argonne National Laboratory by Oak Ridge National Laboratory, May 1977.

Thermal Distribution Costs: unpublished data from Argonne National Laboratory

Economic Results. Incremental breakeven cpaital costs (ΔBECC's) for the baseline options are presented in Table 4-16 by application. The first observation is that all of the ΔBECC's are positive, except for those for the central business district (CBD). The negative values of ΔBECC for the CBD are due to the very high costs of installing and operating an urban thermal distribution system. If these costs were not incurred by the fuel cell DEUS, the economic and thermal dispatch values of ΔBECC would be 179 $/kW and 198 $/kW, respectively. If, alternatively, a thermal distribution system were already "in place" and only its operation and maintenance were charged to the DEUS plant, the corresponding values of ΔBECC would be 106 $/kW and 162 $/kW. It is also clear from Table 4-16 that the hospital and university are economically attractive applications (at least for the specific buildings analyzed here). The values of ΔBECC for these applications are higher than those for any of the other applications, regardless of operating strategy. The reasons for these attractive economic results are the high thermal loads and load factors presented by these applications and the implicit assumption that thermal distribution costs are assumed by the building owners.

With two exceptions the values of ΔBECC for the thermal dispatch are higher than those for economic dispatch. Boiler capital costs are the primary reason for the somewhat lower ΔBECC's of the economic dispatch options. As Table 4-17 shows, the incremental breakeven capital costs for the economic dispatch options are considerably closer to those of the thermal dispatch options before boiler capital costs are subtracted.

The lower values of ΔBECC observed under thermal dispatch operation for the shopping center and the residential/commercial complex are a result of the assumption that all fuel cell capacity was composed of integral multiples of 4.5 MW. Thus, the fuel cells for these two applications were somewhat oversized. When constrained to thermal load following, these DEUS plants incurred significant penalty costs (relative to conventional fuel cells of the same size) for their reduced on-peak operating levels. As the following subsection will show, this effect can be moderated by the incorporation of thermal storage or by the use of a smaller fuel cell and a supplemental boiler.

Table 4-16

ECONOMIC RESULTS FOR BASELINE OPTIONS

APPLICATION	Economic Dispatch		Thermal Dispatch	
	Size of Fuel Cell (MW)	Δ BECC ($/kW)	Size of Fuel Cell (MW)	ΔBECC($/kW)
Hospital	13.5	220	18.0	312
Residential	4.5	99	4.5	113
Shopping Center	4.5	147	9.0	125
Office Building	4.5	147	4.5	167
University	31.5	249	40.5	382
Military Base	4.5	174	4.5	219
Residential/Commercial	4.5	126	9.0	74
Central Business District (Thermal distribution costs included)	58.5	-366	121.5	-65
Central Business District (Thermal distribution costs excluded)	58.5	179	121.5	198

Table 4-17

EFFECT OF BOILER CAPITAL COST ON ECONOMIC DISPATCH RESULTS

APPLICATION	ECONOMIC DISPATCH			THERMAL DISPATCH
	ΔBECC ($/kW)	BOILER COST ($/kW)	ΔBECC & BOILER COST ($/kW)	ΔBECC ($/kW)
Hospital	220	77	297	312
Residential	99	32	131	113
Shopping Center	147	107	254	125
Office Bldg.	147	34	181	167
University	249	75	324	382
Military Base	174	38	212	219
Residential/ Commercial	126	154	280	74
Central Business District	-366	472	106	-64

Energy Supply Results. A summary of the energy supply results for the baseline options is presented in Table 4-18. These results clearly show the range of energy savings and higher annual thermal efficiencies that result from dual energy use operation of fuel cells. It is interesting that the two most economically attractive applications, the hospital and university, are also the most attractive from an energy supply standpoint.

Because under economic dispatch both the DEUS and conventional fuel cells operate on identical schedules, the economic dispatch results offer an excellent basis for comparing the energy use of DEUS versus conventional fuel cells. For most DEUS applications economic dispatch results in fuel savings of from 20 to 25 percent of conventional system fuel consumptions. The corresponding thermal efficiencies for the DEUS are from 60 to 80 percent, while those for the conventional system vary between 50 and 60 percent. The fuel savings and annual efficiencies for the military base, however, are noticeably lower than those for other applications. This is a result of the low, annual thermal load factor for the military base, which has a considerably lower summer air-conditioning load than those of the other applications that were analyzed.

The results for thermal dispatch are also of interest, because they emphasize the strengths and weaknesses of thermal versus economic dispatch from the standpoint of system energy consumption. The "percent energy savings" for the thermal dispatch options vary from 10 to 40 percent, while those for the economic dispatch options vary only from 20 to 30 percent. The higher values of percent savings point to the strength of thermal dispatch operation for applications such as hospitals and universities that require large amounts of thermal energy at relatively high load factors. The lower values of percent savings point to the weakness of the thermal dispatch in serving applications, such as the military base, that have low annual load factors.

Table 4-18

SUMMARY OF ANNUAL ENERGY SUPPLY RESULTS FOR BASELINE OPTIONS

APPLICATION	ECONOMIC DISPATCH					THERMAL DISPATCH				
	Conventional System Fuel Use (10^9 BTU)	Energy Savings Due to DEUS Operation (10^9 BTU)	Per Cent Savings	Average Efficiency		Conventional System Fuel Use (10^9 BTU)	Energy Savings Due to DEUS Operation (10^9 BTU)	Per Cent Savings	Average Efficiency	
				DEUS	Conv.				DEUS	Conv.
Hospital	1183	312	26.4	.78	.57	1541	555	36.0	.82	.52
Residential	311	69.1	22.2	.66	.51	311	74.0	23.8	.67	.51
Shopping Center	357	91.0	25.5	.74	.55	581	94.1	16.2	.58	.48
Office Building	312	63.0	20.2	.64	.51	312	73.6	23.6	.66	.51
University	2891	789	27.3	.81	.59	4043	1529	37.8	.82	.51
Military Base	287	51.6	18.0	.58	.48	287	31.4	10.9	.54	.48
Residential/ Commercial	378	102	27.0	.77	.56	602	109	18.1	.60	.50
Central Business District	5354	1408	26.3	.80	.59	8451	2073	24.5	.68	.51

The "Conventional System" Fuel Use not only includes fuel used by the fuel cell and the conventional boiler, but may also include fuel used by the utility system in generating the deficit power referred to in Section 3.

Two of the decreases that occured in per cent energy savings for thermal dispatch, however, were not entirely due to low load factors. The lower energy savings for the shopping center and the residential/commercial application resulted from a slight oversizing of the fuel cell for these two applications, as explained in the discussion of the economic results above. Although these fuel cells can supply somewhat more thermal energy than the annual peak requirement, they are constrained during most of the year to operate at an even lower level. As a result, the DEUS fuel cell is underutilized relative to the economically-dispatched conventional fuel cell, and deficit electricity must be supplied by the utility to equalize the energy outputs of DEUS and conventional systems. Since this energy is produced at a higher average heat rate, the overall DEUS efficiency decreases accordingly.

Results for Other Load Matching/Decoupling Options

In addition to the baseline economic and thermal dispatch analyses discussed above, analysis were performed to assess the relative attractiveness of various other load matching and decoupling options. The purposes of these options which were discussed earlier in this section, are

- to better fit specific fuel cell sizes to the various application thermal loads
- to give the utility more latitude in specifying the level of DEUS electric generation

The economic and energy supply results for these analyses are presented below.

Economic Results. Values of ΔBECC for the various applications and options are presented in Table 4-19. These results clearly show that such options are worth considering. In six out of eight applications the highest value of ΔBECC occurred for an option other than a baseline option. For economic dispatch, in particular, the use of thermal storage causes an increase in ΔBECC in every case. The obvious reasons for this are that storage allows off-peak thermal loads to be met with on-peak thermal energy that otherwise would have been rejected and

TAble 4-19

ECONOMIC RESULTS FOR ALTERNATIVE LOAD MATCHING/DECOUPLING OPTIONS ($/kW)

APPLICATION	Economic Dispatch			Thermal Dispatch		
	Fuel Cell & Boiler	Fuel Cell & Storage	Fuel Cell & Boiler & Storage	Fuel Cell Only	Fuel Cell & Boiler	Fuel Cell & Storage
Hospital	220	211	249	312	399	321
Residential	99	166	137	113	85	154
Shopping Center	147	177	157	125	165	112
Office Building	147	106	161	167	133	156
University	249	241	251	382	451	368
Military Base	174	127	213	219	176	42
Residential/ Commercial	126	207	198	74	267	167
Central Business District (Thermal distribution costs included)	-366	-16	-79	-65	-243	-173
Central Business District (Thermal distribution costs excluded)	179	221	184	198	304	93

that the associated increase in thermal credits more than offsets the costs of such storage.*

Once again, the university and hospital are distinctly attractive. The military base and the residential/commercial site, on the other hand, range from quite attractive for some options to only marginally attractive for others Apparently, the design and operation of fuel cell dual energy use systems can have a significant effect on their economic attractiveness. The residential, shopping center and office building applications appear less sensitive to the specific option used. If the cost of thermal distribution is ignored, the central business district is more attractive than many other applications. However, its economics are very sensitive to the specific (matching/decoupling) option used.

Energy Supply Results. Annual energy savings for each option and application are presented in Table 4-20. For the most part, the various matching/decoupling options did not result in large changes in the DEUS energy supply results presented above for the baseline options. In a few instances, however, large changes occurred. For example, for both the university and the central business district, the baseline energy savings for economic dispatch were increased by approximately 70 percent when thermal storage was added. This increase is due both to the increased use of fuel cell reject heat and to the decreased use of a supplemental boiler. Another marked change occurs for the central business district, thermal dispatch options. Specifically, energy savings are cut in half by the use of thermal storage. This change is attributable to a familiar problem. In order to produce adequate energy for storage on the day of peak thermal load, it was necessary to use a very large fuel cell. This fuel cell was then underutilized through much of the rest

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* All thermal storage costs used for this study were based on estimates made by Public Service Electric and Gas Company for a previous EPRI study (9). An average cost of $\$2.07/10^3$ Btu of storage was assumed, based on PSE&G estimates for saturated water storage. In order to evaluate the effects of significantly higher storage costs, analyses also were performed under the assumption that the above figure was doubled. Under this assumption, most ΔBECC values decreased by less than 25%. Further, none of the applications became economically unattractive as a result of these storage cost increases.

Table 4-20

ANNUAL ENERGY SAVINGS FOR ALTERNATIVE LOAD MATCHING/DECOUPLING OPTIONS (10^9 Btu)

APPLICATION	Economic Dispatch			Thermal Dispatch		
	Fuel Cell & Boiler	Fuel Cell & Storage	Fuel Cell & Boiler & Storage	Fuel Cell Only	Fuel Cell & Boiler	Fuel Cell & Storage
Hospital	312	253	451	555	583	538
Residential	69.1	46.0	46.0	74.0	74.0	82.8
Shopping Center	91.0	133	108	94.1	113	81.2
Office Building	63.0	88.2	77.3	73.6	73.6	70.1
University	78.9	1323	1055	1529	1505	1455
Military Base	51.6	101	91.8	31.4	92.5	36.0
Residential/ Commercial	102	154	115	109	158	120
Central Business District	1408	2478	2353	2073	2272	1071

of the year. Additionally, it was compared with a large conventional fuel cell that was not underutilized.

Alternative Operating Strategies and Data Assumptions

A number of additional analyses were performed to assess the effects of different operating strategies and data assumptions on the baseline results described above. The pertinent results of these analyses are described below.

Combined Economic and Thermal Dispatch Operation. One alternative to either straight electric or thermal dispatch is combined economic/ thermal dispatch. Under this operating strategy the DEUS operates according to economic dispatch during the on-peak hours and according to thermal dispatch during the off-peak hours. Combined economic/ thermal dispatch was analyzed for three applications including the hospital, university and residential sites. The results of these analyses are shown in Table 4-21. The new operating strategy is considerably more attractive than economic dispatch and slightly more attractive than thermal dispatch from both an economic and an energy supply standpoint. As the results in Tables 4-19 and 4-20 show, other load matching options were analyzed that were more attractive economically, but none resulted in such high annual energy savings. Since this operating strategy likely would be more attractive to the utility owner than thermal dispatch, it is a strategy that should be seriously considered for DEUS operation.

Effect of Higher Fuel Prices. All the results presented previously assume a price of No. 2 fuel oil of 2.45 $\$/10^6$ Btu and a value of thermal energy of 3.00 $\$/10^6$ Btu. Baseline results also were produced for the alternative assumption that fuel oil No. 2 is priced at 3.50 $\$/10^6$ Btu. Under this assumption the value of thermal energy is, at the very least, greater than 4.25 $\$/10^6$ Btu, which is the cost of just the fuel required to produce thermal energy with an oil-fired package boiler at an efficiency of 83 percent.

Table 4-21

RESULTS FOR COMBINED ECONOMIC/THERMAL DISPATCH

APPLICATION	Δ BECC (\$/kW)			ANNUAL ENERGY SAVINGS (10^9Btu)		
	Economic Dispatch	Thermal Dispatch	Economic/ Thermal Dispatch	Economic Dispatch	Thermal Dispatch	Economic/ Thermal Dispatch
Hospital	220	312	342	312	555	600
Residential	99	113	167	69	74	95
University	249	382	395	79	1529	1578

Since the value of thermal energy used in previous analyses was also based (conservatively) on boiler fuel costs, a thermal value of 4.25 $\$/10^6$ Btu was assumed for this analysis. As Table 4-22 shows, higher oil prices result in considerably higher incremental breakeven capital costs for all applications. These increases are due to the higher thermal credits to the DEUS plant that arise from the sale of thermal energy. The conventional plant does not benefit from such credits. One question that arises from this scenario is whether the utility's economic dispatch hours for fuel cells would change after such a fuel price increase. If so, the results might not be so encouraging.

Sensitivity Results

A number of simple sensitivity analyses were performed for both the hospital and the residential site under thermal dispatch operation. These analyses evaluated the sensitivity of ΔBECC to

- Value of Thermal Energy
- Fuel Price
- On-Peak Incremental Energy Cost
- Off-Peak Incremental Energy Cost

The basic sensitivity index was

$$\text{sensitivity} = \frac{\text{Per Cent Change in } \Delta\text{BECC}}{\text{Per Cent Change in Input Variable}} \qquad (4\text{-}2)$$

Sensitivity results are presented in Table 4-23, along with the values of ΔBECC and the respective input variables. In general, the hospital application is less sensitive to all the variables than is the residential site. Given the large size and high load factors of the hospital, this is not surprising. The hospital DEUS is operating at a fairly large profit and thermal credits are high. Recalling from Section 3 that

$$\Delta\text{BECC} = \frac{T_{cr} - \Delta P - \rho}{(E_{cap})\ (CC)\ (CCIF)} \qquad (4\text{-}3)$$

Table 4-22

ECONOMIC EFFECTS OF A FUEL PRICE INCREASE

Operating Strategy	Δ BECC ($/KW)			
	ECONOMIC DISPATCH		THERMAL DISPATCH	
Fuel Price	$2.45/$10^6$Btu	$3.50/$10^6$Btu	$2.45/$10^6$Btu	$3.50/$10^6$Btu
Hospital	220	345	312	440
Residential	99	183	113	283
Shopping Center	147	257	125	290
Office Building	147	224	167	322
University	249	385	382	397
Military Base	174	264	219	369
Residential/ Commercial	126	250	74	246
Central Business District (Thermal distribution costs included)	-366	-235	-64	91
Central Business District (Thermal distribution costs excluded)	179	312	198	354

Table 4-23

BASELINE SENSITIVITY RESULTS FOR TWO APPLICATIONS
(Thermal Dispatch Operation, No Supplemental Boiler)

APPLICATION	VARIABLE	BASE VALUE	Δ BECC ($/kw)			AVERAGE SENSITIVITY
			Base -10%	Base	Base +10%	
HOSPITAL	Off Peak Incremental Energy Cost (mills/kw)	21.30	330.61	312.00	288.71	0.67
	On Peak Incremental Energy Cost (mills/kw)	30.40	290.06	312.00	329.25	0.63
	Fuel Price ($\$10^6$ Btu)	2.45	319.00	312.00	306.00	0.21
	Value of Thermal Energy ($\$10^6$ Btu)	3.00	275.00	312.00	350.00	1.20
RESIDENTIAL	Off Peak Incremental Energy Cost (mills/kw)	21.30	119.31	113.00	101.26	0.80
	On Peak Incremental Energy Cost (mills/kw)	30.40	79.78	113.00	140.79	2.70
	Fuel Price ($\$10^6$ Btu)	2.45	102.00	113.00	125.00	1.02
	Value of Thermal Energy ($\$10^6$ Btu)	3.00	87.10	113.00	140.00	2.34

the hospital results seem quite understandable. Because T_{cr} (the annual credit for thermal energy sales) is so large, it dominates the numerator of Equation 4-3. Thus, ΔBECC is not very sensitive to those variables which affect only the increased production costs or penalty costs. Given that T_{cr} is large relative to ΔP and ρ (the annual production cost increase and penalty cost, respectively), however, it is quite reasonable to expect a sensitivity of approximately one to the value of thermal energy.

As Table 4-23 shows, ΔBECC for the residential site is more sensitive to all imputs and is particularly sensitive to on-peak incremental energy cost and the value of thermal energy. Because the residential application has a lower average load and load factor, T_{cr}, ΔP and ρ are all the same order of magnitude.

Thus, the percent variations for the numerator of Equation 4-3 may be larger than the percent variations made in the input variables themselves. The two highest sensitivities are the on-peak incremental energy cost, which affects ρ in Equation 4-3, and the value of thermal energy, which affects T_{cr}. In conclusion, it appears that the more promising an application is economically, the less sensitive it will be to the assumed values of these input data.

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Section 5

INDUSTRIAL APPLICATIONS

SECTION SUMMARY

An analysis of the process energy requirements in the industrial sector was performed for 4 digit Standard Industrial Classification (SIC) groups. Eleven industries were selected for detailed evaluation, and data for typical plants in these industries were developed. DEUS fuel cell systems operating in the economic dispatch mode and the thermal load following mode were examined for each typical plant. The results are summarized below:

- All of the typical plants examined are promising applications for DEUS fuel cells. Incremental Breakeven Capital Costs (ΔBECC) ranging from \$70/kW to over \$400/kW were obtained under the economic dispatch case
- DEUS fuel cells consistently show greater energy utilization efficiencies and significant fuel savings in the economic dispatch mode.
- The thermal load following mode can result in higher values of ΔBECC and higher efficiency and fuel savings However, some fuel displacement may take place if the DEUS fuel cell operates in the off-peak hours for plants with two or three shift operation, resulting in reduced use of baseload coal or nuclear fuel and increased use of petroleum based fuel.
- Modification of the Type I - phosphoric acid fuel cell to provide additional steam (Configuration C, Option II) can be economically very attractive relative to Configuration B.
- The Type II - molten carbonate fuel cell offers the advantage of higher quality thermal energy and may therefore be applicable to a larger number of industries than the Type I - phosphoric acid fuel cell. However, the amount of thermal energy at the higher temperature range is relatively small, and the total thermal energy available is less than that in Type I (because Type I has a lower heat rate); therefore the Type II - molten carbonate fuel cell may not be significantly more attractive for DEUS operation than the Type I-phosphoric acid fuel cell.

- The value of thermal energy to the potential industrial user is the most important parameter affecting the economic viability of a DEUS fuel cell.
- In some industries, significant quantities of waste heat may be available and would be preferred over thermal energy from a DEUS fuel cell. However, the DEUS fuel cell may still be attractive if the quantities of waste heat available are not sufficient or if the cost of waste heat recovery is high.

The following pages describe the identification of industrial applications, screening and selection, methodology, for evaluating alternative design and operating strategies, and the results of the evaluation process. Sensitivity analysis results are also described.

IDENTIFICATION OF POTENTIAL APPLICATIONS

Industrial Process Heat Requirements Data Sources

The industrial sector represents a major user of thermal energy. The quality and quantity of thermal energy required vary significantly from industry group to industry group. The identification of potential applications for thermal energy from DEUS fuel cells, therefore, requires disaggregation of thermal energy requirements by industry group and temperature level.

In this study industrial applications were identified at the four digit SIC (Standard Industrial Classification) level (2). Since there are about 450 SIC groups at the four-digit level, the study attempted to identify, through a structured screening process, those industries which appeared to be promising for application of DEUS fuel cells. The data base, methodology and results of the screening process are described in this section.

Most information on industrial thermal energy requirements is available only at an aggregated level insufficient for the purposes of this study. For example, the Census and Survey of Manufacturers (3), (4) report information on energy consumption at the 4-digit SIC level, but do not provide data on the end uses, so that information on thermal needs cannot be obtained from this source. Other sources such as the Energy Consumption Data Base (ECDB) of the U.S. Department of Energy(5), and the initial stage of the Drexel Industrial Applications Study (6) report data on process heat requirements but only at the 2-digit level. (An illustration of the 2,3, 4-digit SIC codes is presented in Table 5-1 for one major industry group.)

Table 5-1

ILLUSTRATION OF STANDARD INDUSTRIAL CLASSIFICATION (SIC) CODES (Food and Kindred Products Group (SIC 20)

SIC CODE			
TWO DIGIT	THREE DIGIT	FOUR DIGIT	INDUSTRY NAME
20			Food and Kindred Products
	201		Meat Products
		2011	Meatpacking Plants
		2013	Sausages, Other Prepared Meats
		2016	Poultry Dressing Plants
		2017	Poultry and Egg Processing
	202		Dairy Products
		2021	Creamery Butter
		2022	Cheese, Natural and Processed
		2023	Condensed and Evaporated Milk
		2024	Ice Cream and Frozen Desserts
		2026	Fluid Milk
	203		Preserved Fruits and Vegetables
		2032	Canned Specialties
		2033	Canned Fruits and Vegetables
		2034	Dehyd. Fruits, Vegetables, Soup
		2035	Pickles, Sauces, Salad Dressing
		2037	Frozen Fruits and Vegetables
		2038	Frozen Specialties
	204		Grain Mill Products

Some information has been developed on process heat requirements at the 4-digit level for studies of solar industrial process heating (7), (8), and current efforts are underway to develop a very detailed data base on end use energy consumption at the 4-digit level as a part of the current stage of the Drexel Industrial Applications Study (9). However, this information will not be available until Spring, 1979.

Since none of the existing sources could provide the information on thermal energy needs at the 4-digit level, a special study was performed by General Energy Associates in their capacity as a subcontractor on this effort (10).

Initial List of Applications

Initially, the 4-digit SIC groups were ranked according to their total annual energy consumption, and the top 76 most energy intensive industries were identified. These 76 industries accounted for over 90% of the total industrial process heat requirements. For each of these 76 industries, the total process heat requirements were disaggregated in five temperature ranges:

- less than 212°F
- 212-235°F
- 350-550°F
- 550-1000°F
- greater than 1000°F

This classification was based on the availability of thermal energy (by quality) from the Type I and Type II fuel cell.

SCREENING PROCESS AND SELECTED APPLICATIONS

The potential viability of DEUS fuel cells in industrial applications depends on a number of technical and economic factors. Technical factors include the quality and quantity of thermal energy needed vs quality and quantity of thermal energy available from the fuel cell, temporal profile of thermal needs and availability, and technical options for matching/decoupling. Economic factors include the value of thermal energy, capital and operating costs of heat recovery and distribution (including any economic penalities associated with non-optimal electric generation), cost of fuel, etc.

Since it was impossible to evaluate all 76 industrial applications within the time and resource constraints of this study, a sequential screening process was employed to identify the most promising applications. The first step (preliminary screening) involved an evaluation of the relative quantities of thermal energy required in the different temperature ranges. A simple weighting procedure was developed to calculate a weighted average thermal energy requirement for each industry. Two sets of weighting criteria were used, based on relative proportions of thermal energy available in each temperature range from the Type I and Type II fuel cells. These weights were applied to the thermal energy requirements in the appropriate temperature range to develop a weighted average, and a ranking was determined based on the Type I and Type II weights.

The top 20 industries based on the Type I weights and the top 20 based on the Type II weights were identified. Since 13 industries appeared on both lists, the combination gave a list of 27 industries. The 27 industries and their process heat requirements by temperature range are shown in Table 5-2.

In order to select the most promising applications from the list of 27 industries, the following questions were addressed.

- Are the thermal requirements of the industry compatible with the fuel cell thermal energy characteristics?
- Is the size of the application at least as large as the 4.5 MW Demonstrator?
- Are there enough applications nationally?

Information on the number of plants, distribution by plant size, number of operating shifts, annual operating hours, and average and peak electric requirements was developed for the 27 industries, and additional screening steps were employed to answer these questions. The Type I - phosphoric acid fuel cell can provid thermal energy only in the first two temperature ranges (hot water at 160°F and steam at 350°F as described in Section 2). The relative proportions of energy available in the low (<212°F) and high (212-350°F) temperature ranges are 79% and 21% respectively (steam to hot water ratio of 0.27) under Configuration B. If the industry's thermal energy needs in these two temperature ranges are exactly in these proportions, then all of the thermal energy can be utilized. If the industry process heat requirements are more than 79% in the low range (range 1) and less than 21% in the high range (range 2), some of the process heat from the range 2

Table 5-2

PROCESS HEAT REQUIREMENTS (1974) FOR 27 INDUSTRIES FROM PRELIMINARY SCREENING

SIC CODE	INDUSTRY	TOTAL PROCESS HEAT REQUIREMENTS (TRILLION Btu)					
		<212° F	212-350° F	350-550° F	550-1000° F	>1000° F	TOTAL
1211	Bituminous Coal	18.00					18.00
2011,13	Meat and Sausage	45.40		1.10			46.50
2022	Natural Cheese	15.00					15.00
2023	Cond. and Evap. Milk	8.13	0.54	3.58			12.25
2046	Wet Corn Milling	3.96	11.50			2.93	18.39
2062	Cane Sugar Refining	4.77	26.40		2.00	2.00	35.17
2063	Beet Sugar	14.50	47.30			2.98	64.78
2075	Soybean Oil	4.35	12.10				16.45
2085	Distilled Liquors	3.16	18.20				21.36
2261	Cotton Finishing	19.90	22.20				42.10
2262	Synthetic Finishing	51.10	23.20				74.30
2421	Saw and Planning Mills		63.40				63.40
2435	Plywood		50.60				50.60
2436	Veneer	57.80					57.80
2511	Wooden Furniture	9.50					9.50
2611,21,31,61	Pulp and Paper Mills	175.00	547.00	253.00		96.00	1071.00
2812	Alkalies and Chlorine		82.10				82.10
28195	Alumina		113.20			35.30	148.50
2822	Synthetic Rubber	10.60					10.60
2823	Cellulosic Fibers		23.50	94.50			118.00
2824	Non-Cellulosic Fibers	75.40					75.40
2865	Cyclic Crudes and Intermediates		38.50				38.50
2869	Organic Chemicals		27.00				27.00
2911	Petroleum Refining	59.00	60.00		1602.00	695.00	2416.00
2951	Paving Mixtures		93.00				93.00
3271	Concrete Blocks	12.30		5.42			17.72
3321,22,23	Iron and Steel Foundries	151.00		117.70	8.00	154.00	430.70

can be used to satisfy the needs in the range 1. But if the industry process heat requirements are less than 79% in the range 1 and greater than 21% in the range 2, there will be more energy available in the low temperature range than is needed. This energy cannot be used for the needs in the range 2. In such a case, some rejection of heat (in the low temperature range) will be inevitable. This will decrease the overall energy utilization efficiency of the fuel cell. It should be noted that any industry process heat requirements at temperatures above 350°F cannot be satisfied by the Type I - phosphoric acid fuel cell, and a supplementary boiler (or furnace) is essential.

It should also be noted that, as described in Section 2, the thermal energy output characteristics of the fuel cell can be changed to get additional steam at 350°F. Configuration C, Option II, yields a ratio of 26% steam to 74% hot water, or a steam to hot water ratio of 0.35.

Industries having ratios of steam (temperature range 2) to hot water (temperature range 1) needs of about 0.27 to 0.35 will be excellent candidates for fuel cell reject heat utilization. This ratio is useful in addressing the first question above.

The other two questions require an analysis of typical plants within each industry. Information on plant size distribution was used to determine the typical sizes and numbers of fuel cells required. Table 5-3 shows the information on plant size distribution. Table 5-4 shows the percent of total process energy used by each group of plants. Using this information, the thermal energy requirements of typical small, medium and large plants in each SIC were calculated and typical fuel cell sizes and number of plants were determined.

Based on the analysis of the information on typical fuel cell sizes, number of plants and the ratio of thermal energy requirements in the two temperature ranges, the industries were ranked as shown in Table 5-5. Only industries having at least 15 plants and a size of at least 5 MW were selected. The final list of 11 selected industries is shown in Table 5-6.

Table 5-3

PLANT SIZE DISTRIBUTION FOR INDUSTRIAL APPLICATIONS

SIC CODE	INDUSTRY NAME	NUMBER OF PLANTS *			
		SMALL	MEDIUM	LARGE	TOTAL
1211	Bituminous Coal	30	46	30	106
2011,13	Meat and Sausage	2374	976	451	3801
2022	Natural Cheese	703	277	57	1037
2023	Condensed and Evaporated Milk	106	122	22	250
2046	Wet Corn Milling	13	9	15	37
2062	Cane Sugar Refining	5	8	18	31
2063	Beet Sugar	7	54	1	62
2075	Soybean Oil	23	53	34	110
2085	Distilled Liquors	22	46	37	105
2261	Cotton Finishing	73	54	50	177
2262	Synthetic Finishing	72	99	99	270
2421	Saw and Planing Mills	7066	1528	381	8975
2435	Plywood	112	178	76	366
2436	Veneer	7	66	151	224
2511	Wooden Furniture	1558	536	311	2405
2611,21, 31, 61	Pulp and Paper Mills	125	219	446	790
2812	Alkalies & Chlorine	9	16	25	50
28195	Alumina	3	4	3	10
2822	Synthetic Rubber	25	12	22	59
2823	Cellulosic Fibers	6	2	12	20
2824	Non-Cellulosic Fibers	6	12	46	64
2865	Cyclic Crudes and Intermediates	55	55	60	170
2869	Organic Chemicals	224	141	161	526
2911	Petroleum Refining	47	103	182	332
2951	Paving Mixtures	747	144	15	906
3271	Concrete Blocks	857	358	9	1224
3321,22, 23	Iron and Steel Foundries	386	629	528	1543

Source: General Energy Associates, Reference (10)
* Notes: Small = less than 20 employees
Medium = 20 to 99 employees
Large = 100 or more employees

Table 5-4

PERCENT OF ENERGY USED IN EACH SIZE GROUP OF PLANTS FOR INDUSTRIAL APPLICATIONS

SIC CODE	INDUSTRY NAME	PERCENT OF PROCESS HEAT REQUIREMENTS		
		SMALL	MEDIUM	LARGE
1211	Bituminous Coal	11.0	29.0	60.0
2011,13	Meat and Sausage	5.6	20.3	74.1
2022	Natural Cheese	15.5	35.4	49.1
2023	Condensed and Evaporated Milk	8.3	52.5	39.2
2046	Wet Corn Milling	1.2	4.8	94.0
2062	Cane Sugar Refining	0.2	5.8	87.0
2063	Beet Sugar	0.2	92.1	7.7
2075	Soybean Oil	1.2	28.8	70.0
2085	Distilled Liquors	1.3	13.1	85.6
2261	Cotton Finishing	2.3	11.5	88.2
2262	Synthetic Finishing	1.3	13.8	84.9
2421	Saw and Planing Mills	15.0	36.7	48.3
2435	Plywood	3.2	37.1	59.7
2436	Veneer	0.2	8.3	91.5
2511	Wooden Furniture	6.3	17.7	76.0
2611,21 31,61	Pulp and Paper Mills	0.4	5.6	94.0
2812	Alkalies & Chlorine	1.0	6.3	92.7
28195	Aluminas	2.0	11.7	86.3
2822	Synthetic Rubber	3.7	3.7	92.6
2823	Cellulosic Fibers	0.7	0.7	98.6
2824	Non-Cellulosic Fibers	0.1	0.9	99.0
2865	Cyclic Crudes and Intermediates	1.6	10.2	88.2
2869	Organic Chemicals	1.4	6.2	92.4
2911	Petroleum Refining	0.6	5.0	94.4
2951	Paving Mixtures	36.0	30.0	34.0
3271	Concrete Blocks	33.5	60.5	6.0
3321, 22, 23	Iron and Steel Found	1.3	12.9	85.8

Source: General Energy Associates, Reference (10)

Table 5-5

RANKING OF INDUSTRY PLANTS WITH HIGH POTENTIAL FOR DEUS FUEL CELL APPLICATION

RANK	SIC CODE	PLANT SIZE	INDUSTRY NAME	TYPICAL** FUEL CELL SIZE (MW)	NUMBER OF PLANTS
1	28195	Large	Alumina	2300	3
2	2063	Large	Beet Sugar	260	1
3	28195	Medium	Alumina	235	4
4	2951	Large	Paving Mixtures	151	15
5	2823	Large	Cellulosic Manmade Fibers	139	12
6	2812	Large	Alkalies and Chlorine	100	25
7	2062	Large	Cane Sugar Refining	98	18
8	2600*	Large	Pulp and Paper Mills	90	446
9	2063	Medium	Beet Sugar	58	54
10	28195	Small	Alumina	54	3
11	2865	Large	Cyclic crudes and Intermediates	40	60
12	2261	Large	Finishing Plants, Cotton	27	50
13	2911	Large	Petroleum Refining	22	180
14	2262	Large	Finishing Plants, Synthetic	14	99
15	2824	Large	NonCellulosic Fibers	33	46
16	2261	Medium	Finishing Plants, Cotton	3	54
17	2262	Medium	Finishing Plants, Synthetic	2	99
18	2085	Large	Distilled Liquors	30	37
19	2075	Large	Soybean Oil Mills	17	34
20	2600*	Medium	Pulp and Paper Mills	1	219
21	2062	Medium	Cane Sugar Refining	1	8
22	2435	Large	Plywood	28	76
23	2812	Medium	Alkalies and Chlorine	23	16

* SIC's 2611, 21, 31, 61 are denoted by SIC 2600 in this and subsequent tables.

** Based on thermal requirements.

Table 5-6

INDUSTRIAL PLANTS SELECTED FOR DEUS FUEL CELL EVALUATION

SIC NO.	INDUSTRY	SIZE OF PLANT	NUMBER OF PLANTS
2951	Paving Mixtures	Large	15
2812	Alkalies and Chlorine	Large	25
2600*	Pulp and Paper Mills, etc.	Large	446
2062	Cane Sugar Refining	Large	18
2063	Beet Sugar	Medium	54
2865	Cyclic Crudes and Intermediates	Large	60
2261	Finishing Plants, Cotton	Large	50
2911	Petroleum Refining	Large	180
2262	Finishing Plants, Synthetic	Large	99
2824	Non-Cellulosic Fibers	Large	41
2085	Distilled Liquors	Large	37

* 2600 denotes 2611, 21, 31, 61

CHARACTERISTICS OF SELECTED APPLICATIONS

A brief description of the industries selected for further analysis is given in Table 5-7. These plants represent a total of over 1000 applications with each one being at least 5 MW and some as large as 150 MW. The exact size of the DEUS fuel cell installation would depend on the sizing and operational options (as discussed below).

Tables 5-8 and 5-9 show the major characteristics of the selected applications. Figure 5-1 shows illustrative temporal profiles for a selected industry.

It should be pointed out that, in some of the selected industries, there is a significant requirement for thermal energy at temperature levels in excess of 1000°F. In such situations, it is possible that there may be significant amounts of waste heat available, which can be recovered and utilized for lower temperature applications. Estimation of the availability and quality of waste heat and the costs of its recovery and utilization, were beyond the scope of this effort. If reliable data on waste heat are available, they can be incorporated into this analysis, as described in a subsequent subsection.

Table 5-7

DESCRIPTION OF INDUSTRIES SELECTED FOR ANALYSIS

SIC Code	Name & Description
2062	Cane Sugar Refining Establishments primarily engaged in refining purchased raw cane sugar and sirup.
2063	Beet Sugar Establishments primarily engaged in manufacturing sugar from sugar beets.
2085	Distilled, Rectified, and Blended Liquors Establishments primarily engaged in manufacturing alcoholic liquors by distillation and rectification, and in manufacturing cordials and alcoholic cocktails by blending processes or by mixing liquors and other ingredients.
2261	Finishers of Broad Woven Fabrics of Cotton Establishments primarily engaged in finishing purchased cotton broad woven fabrics or finishing such fabrics on a commission basis. These finishing operations include bleaching, dyeing, printing (roller, screen, flock, plisse), and other mechanical finishing such as preshrinking, calendering and napping. This industry also includes the shrinking and sponging of cloth for the trade, and chemical finishing for water repellency, fire resistance, and mildew proofing.
2262	Finishers of Broad Woven Fabrics of Man-Made Fiber and Silk Establishments primarily engaged in finishing purchased man-made fiber and silk broad woven fabrics or finishing such fabrics on a commission basis. These finishing operations include bleaching, dyeing, printing (roller, screen, flock, plisse), and other mechanical finishing such as preshrinking, calendering, and napping.
2600 (2611, 2621, 2631, & 2661)	Paper & Pulp Mills, etc. Establishments primarily engaged in manufacturing pulp from wood or other materials such as rags, linters, waste paper, and straw. Logging camps operated by pulp mills, and not separately reported, are also included in this industry.
2621	Paper Mills, Except Building Paper Mills Establishments primarily engaged in manufacturing paper from wood pulp and other fibers, and which may also manufacture converted paper products.
2631	Paper Board Mills Establishments primarily engaged in manufacturing paperboard, including paperboard coated on the paperboard machine, from wood pulp and other fibers; and which may also manufacture converted paperboard products.

Continued

Table 5-7 Continued

2661	Building Paper & Board Mills Industry; where separately reported they are classified in industry 2611.
2812	Alkalies and Chlorine Establishments primarily engaged in manufacturing alkalies and chlorine.
2824	Synthetic Organic Fibers, Except Cellulosic Establishments primarily engaged in manufacturing synthetic organic fibers, except cellulosic (including those of regenerated proteins, and of polymers or copolymers of such components as vinyl chloride, vinylidene chloride, linear esters, vinyl alcohols, acrylonitrile, ethylenes, amides, and related polymeric materials) in the form of monofilament, yarn, staple or tow suitable for further manufacturing on spindles, looms, knitting machines or other textile processing equipment.
2865	Cyclic (Coal Tar) Crudes, and Cyclic Intermediates, Dyes, and Organic Pigments (Lakes and Toners)
	Establishments primarily engaged in manufacturing coal tar crudes and cyclic organic intermediates, dyes, color lakes and toners. Important products of this industry include: (1) derivatives of benzene, toluene, naphthalene, anthracene, pyridine, carbazole, and other cyclic chemical products; (2) synthetic organic dyes; (3) synthetic organic pigments; and (4) cyclic (coal tar) crudes, such as light oils and light oil products; coal tar acids; and products of medium and heavy oil such as creosote oil, naphthalene, anthracene, and their higher homologues, and tar.
2911	Petroleum Refining Establishments primarily engaged in producing gasoline, kerosene, distillate fuel oils, residual fuel oils, lubricants and other products from crude petroleum and its fractionation products, through straight distilation of crude oil, redistilation of unfinished petroleum derivatives, cracking or other processes.
2951	Paving Mixtures and Blocks Establishments primarily engaged in manufacturing asphalt and tar paving mixtures; and paving blocks made of asphalt, creosoted wood, and various compositions of asphalt or tar with other materials.

Source: U. S. Department of Commerce, <u>Standard Industrial Classification Manual</u>

Table 5-8

DAILY AND ANNUAL OPERATING CHARACTERISTICS (1974)
OF SELECTED INDUSTRIAL PLANTS

SIC NO.	INDUSTRY	SIZE OF PLANT	ESTIMATED SHIFT OPERATIONS	ANNUAL OPERATION (Hours/Yr)
2062	Cane Sugar Refining	Large	2-3	5500
2063	Beet Sugar	Medium	1-2	4000
2085	Distilled Liquors	Large	2-3	4500
2261	Finishing Plants, Cotton	Large	2-3	5800
2262	Finishing Plants, Synthetic	Large	2-3	5800
2600*	Pulp and Paper Mills	Large	3	7500
2812	Alkalies and Chlorine	Large	3	5600
2824	Non-Cellulosic Fibers	Large	2-3	5500
2865	Cyclic Crudes and Intermediates	Large	3	6200
2911	Petroleum Refining	Large	3	7500
2951	Paving Mixtures	Large	1-1.5	2600

* 2600 represents 2611, 21, 31, 61

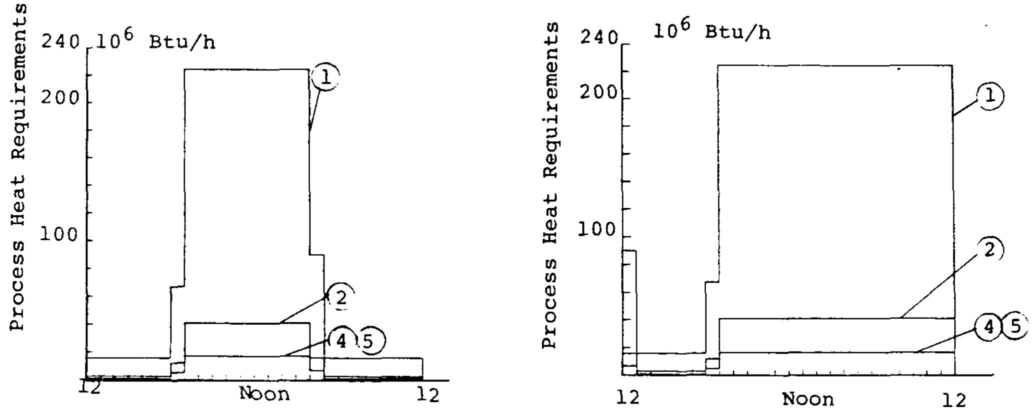
Source - General Energy Associates, Reference (10)

Table 5-9

ENERGY REQUIREMENTS (1974) FOR SELECTED INDUSTRIAL PLANTS

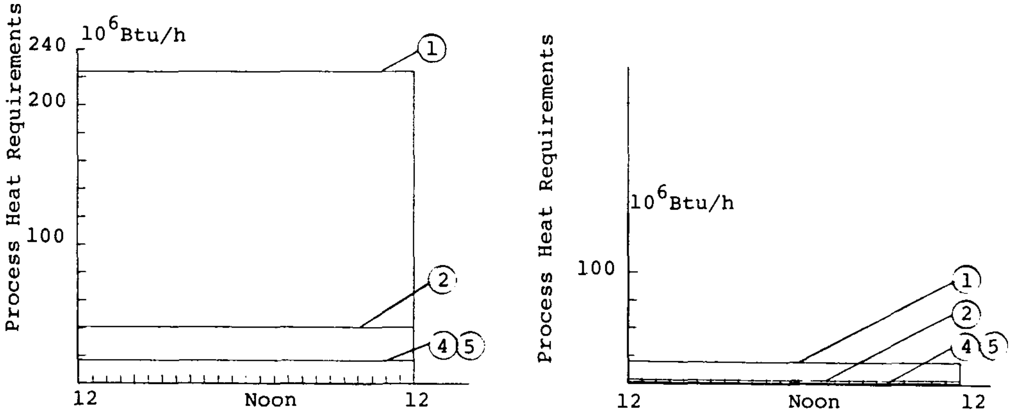
SIC CODE	INDUSTRY NAME	Plant Thermal Energy Requirements (10^6 Btu/hr)						Plant Electric Requirements (kW)
		< 212°F	212-350°F	350-500°F	500-1000°F	1000°F	TOTAL	
2062	Cane Sugar Refining	45	250	-	18	13	329	1275
2063	Beet Sugar	279	910	-	-	57	1247	3775
2085	Distilled Liquors	16	93	-	-	-	110	5057
2261	Finishing Plants, Cotton	59	66	-	-	-	125	1443
2262	Finishing Plants, Synthetic	75	34	-	-	-	109	1343
2600	Paper and Pulp Mills	49	153	71	-	26	300	9111
2812	Alkalies and Chlorine	-	543	-	-	-	543	82,674
2824	Non-Cellulosic Fibers	295	-	-	-		295	26,765
2865	Cyclic Crudes and Intermediates	-	91	-	-	-	91	10,121
2911	Petroleum Refining	40	41	-	1107	436	1626	17,859
2951	Paving Mixtures	-	810	-	-	-	810	5176

Source: General Energy Associates, Reference (10)



(a) One-Shift Operation

(c) Two-Shift Operation



(b) Three-Shift Operation

(d) Off-Day Operation

LEGEND:

1	Process Heat Requirements	212°F
2	" "	212-350°F
3*	" "	350-550°F
4	" "	550-1000°F
5	" "	1000°F

* no process heat required in this range for this industry

Figure 5-1. Illustration of Temporal Profiles for Industry SIC 2062, Cane Sugar Refining.

DEUS LOAD MATCHING/DECOUPLING OPTIONS

In this section, different options for thermal and electric load matching and/or decoupling are identified and discussed. Each option is defined by the specification of a plant design and an operating strategy. In this subsection, the major considerations influencing fuel cell sizing are first discussed. Generic strategies for operating the fuel cell DEUS plant are then described. The load matching/decoupling options are then synthesized and analyzed for the selected industrial applications.

DEUS Plant Design Alternatives

Since DEUS plants are utility-owned and grid-connected the plant size can be independent of the plant electric requirements. The important design consideration is therefore the thermal energy requirements. Utility-owned DEUS plants must provide the entire thermal needs for a given application, using combinations of supplementary boiler, thermal storage, and fuel cells.

The sizing of the plant will require consideration of the thermal needs in the two temperature ranges provided by the fuel cell (less than $212^{\circ}F$ and $212-350^{\circ}F$). If the plant requires thermal energy of any higher quality, a supplementary boiler is mandatory. The fuel cell DEUS plant can be sized to meet either the peak or the average thermal requirements in either of the two temperature ranges. If the fuel cell size does not provide the entire thermal needs the DEUS plant will have to include a supplementary boiler, thermal storage and/or heat pump.

Four generic sizing alternatives were considered for industrial applications:

- fuel cell with supplementary boiler
- fuel cell and thermal storage
- fuel cell and heat pump
- fuel cell, thermal storage and heat pump

Table 5-10 illustrates these options.

Each of these options has its unique characteristics and attributes. Generally, in industrial plants, if a DEUS plant is to be designed to satisfy all thermal requirements from a fuel cell, it may have to be oversized and will have to operate and produce electricity during

Table 5-10

DEUS PLANT DESIGN ALTERNATIVES

ALTERNATIVES	REMARKS
Fuel Cell and Boiler	A number of different combinations are possible, depending on the thermal requirements in the two temperature ranges.
Fuel Cell and Thermal Storage	Storage can be used to make use of thermal energy generated at a time when it is not needed. Two different sets of storage devices may be required, one for each temperature level.
Fuel Cell and Heat Pump	Heat pump can be used to upgrade low temperature thermal energy to high temperature. May be useful when proportion of high temperature requirements is higher than fuel cell thermal energy supplied, if suitable heat pump can be found.
Fuel Cell, Thermal Storage and Heat Pump	Combination could provide greater flexibility but at a higher capital cost.

off-peak and off-day operations. This may lead to oversizing and inefficient operation. It is therefore desirable to include a supplementary boiler, thermal storage or both. Also, since two different temperature levels are involved, a heat pump may be used for upgrading the thermal quality from one temperature to the other.

The advantages of a supplemental boiler are that it can supply the thermal load during scheduled or forced outages of the DEUS fuel cell and can at other times be operated in parallel with the fuel cell to meet thermal peaks. Thermal storage offers a somewhat different opportunity. When process heat requirements fluctuate, thermal storage can be incorporated and a fuel cell with a boiler of a smaller size would result. This can improve the fuel utilization efficiency. The fuel cell can be operated at full rated load during peak hours and the excess thermal energy can be stored. During off-peak hours or at times of deficit of thermal energy production, this energy can be retrieved from storage. The storage can be set up for either or both temperature ranges. One advantage of thermal storage is that it allows the DEUS plant to operate at higher electrical output levels than would be required to meet the instantaneous thermal load without wasting the thermal energy produced. Thus, the plant is freer to respond to the electrical demands of the utility system.

In industrial plants with insignificant process heat requirements in the low temperature range, a large fraction of the fuel cell thermal output may be rejected. If a suitable industrial heat pump is available and is incorporated into the DEUS fuel cell system, all or part of the low grade heat can be upgraded and used. This option can improve the energy utilization efficiency. However, since electricity would be used in the heat pump, the economic viability will depend on the achievement of a high COP (Coefficient of Performance) for the heat pump.

DEUS Plant Operating Strategies

Depending on the DEUS plant design selected, a number of operating strategies are feasible. Table 5-11 shows the different operating strategies. The first strategy, which was described previously in Section 3, is to operate the fuel cell according to the economic dispatch schedule of the host utility. All thermal energy generated as a by-product of such operation would be available for use in meeting the site thermal needs. Any additional thermal energy required by the site would have to be met by a boiler or storage. Depending on the incremental cost characteristics of the specific fuel cell plant relative to the rest of the utility system, it might be scheduled either as an intermediate load plant or a peaking plant. The advantage of the economic dispatch strategy is that it permits the utility to incorporate the DEUS plant into its system exactly as it would incorporate any other plant. Thus, present operating procedures need not be changed to incorporate the DEUS fuel cell plants, which will at least initially constitute a very small fraction of the utility's overall generating mix.

Table 5-11

POSSIBLE OPERATING STRATEGIES FOR THE HOURLY OPERATION OF THE FUEL CELL

Serial No.	Description of Strategy
1	Electric Utility Economic Dispatch Schedule
2	Operate at full rated load
3	Operate at Standby (25% rated power)
4	Meet the process heat requirement in both the temperature ranges
5	Meet the process heat requirements in the temperature range 1 (< 212° F)
6	Meet the process heat requirements in the temperature range 2 (212-350° F)
7	Meet the process heat requirement in the temperature range 1, but at least operate at economic dispatch level
8	Meet the process heat requirement in the temperature range 2, but at least operate at economic dispatch level

All other strategies depart from economic dispatch, and electricity production is subject to penalty costs due to non-optimal generation from the conventional electric utility perspective. Strategies 4,5, and 6 meet the process heat requirements and have the effect of maximum utilization of thermal energy and increased thermal credits. However, the credits have to be balanced against the penalty costs to assess the total economic viability. Strategies 7 and 8 are combintion strategies, while Strategies 2 and 3 are simple and self-explanatory.

In order to simplify the analysis, only two basic operating strategies, namely economic and thermal dispatch, were investigated. Both of these operating strategies were discussed previously in Section 3. Thermal dispatch is less straightforward in this case than for building systems, however, because for those industrial applications selected most thermal loads fall within two temperature ranges (i.e. temperatures less than 212°F and temperatures between 212 and 350°F). Thus, there is a question as to the specific thermal load to "follow" under thermal dispatch. However, each application was evaluated for both a DEUS fuel cell sized to the low temperature requirement and a DEUS fuel cell sized to the high temperature requirement. Therefore, thermal dispatch operation was simply defined as Strategy 4 (see Table 5-11) for the former sizing alternative and Strategy 5 for the latter sizing alternative. The obvious advantages of thermal dispatch operation are that it minimizes the requirement for supplemental thermal supply and maximizes the amount of cogenerated thermal energy.

Combining each of the four design alternatives presented above with each of the primary operating strategies, a matrix of options for thermal/electric load matching/decoupling can be constructed. Such a matrix is presented in Table 5-12.

Table 5-12

OPTIONS FOR THERMAL AND ELECTRICAL LOAD MATCHING/DECOUPLING

Design Alternative	Operating Strategy	
	Thermal load following	Economic Dispatch
Fuel Cell with Boiler	Electricity strictly a by-product	DEUS operates only during utility peak demand hours. A boiler is needed to make up the thermal requirements.
Fuel Cell and Thermal Storage	Storage used to meet some of the thermal requirements during peaks	Storage available for use of thermal energy in the off-peak hours.
Fuel Cell and Heat Pump	Low temperature thermal energy is upgraded for use in the high temperature needs.	Same as for the thermal load following.
Fuel Cell, Heat Pump and Thermal Storage	Thermal energy drawn from storage during peaks; heat pump used to upgrade the low temperature heat for high temperatures.	Heat pump more economical during utility off-peak; thermal storage for off-peak use.

APPLICATIONS ANALYSIS

Each selected application was analyzed by calculating the sizing and simulating the operation of the fuel cell and industrial plant and matching the supplies and demands of thermal energy in the two temperature ranges on an hourly basis. An overview of the approach is shown in Figure 5-2.

For such an analysis, the data requirements were:

- industry operational characteristics
- fuel cell characteristics and
- electric utility load and incremental electric energy cost characteristics.

Industry Characteristics

For each industry, the energy demand data were disaggregated to the plant level. Hourly and seasonal variations in process heat requirements were estimated. Typical thermal load profiles for one industry for different numbers of shifts were shown previously in Figure 5-1. Ordinarily, the plant would operate an industrial boiler to supply their thermal needs. Therefore, boiler costs and efficiencies were assumed, and a value of thermal energy was determined for each industrial plant. Table 5-13 shows the calculated values of thermal energy for various industries.

Fuel Cell Characteristics

Heat rate and thermal outputs for various operating levels for the Type I - phosphoric acid fuel cell, Configuration B, were used for the baseline results. Configuration C and its characteristics were also considered for some additional results.

Electric Utility Characteristics

The hourly economic dispatch schedule for a reference electric utility was based on the PSE&G Study (11). This schedule defined operating strategies for the fuel cell under economic dispatch. Also, the incremental costs of electricity at various times of day were provided for the calculation of electrical energy credits or penalties.

Supplementary Boiler Requirements

The process heat requirements not met by the fuel cell were assumed to be provided by a supplementary boiler. The cost and efficiency characteristics of this boiler were supplied.

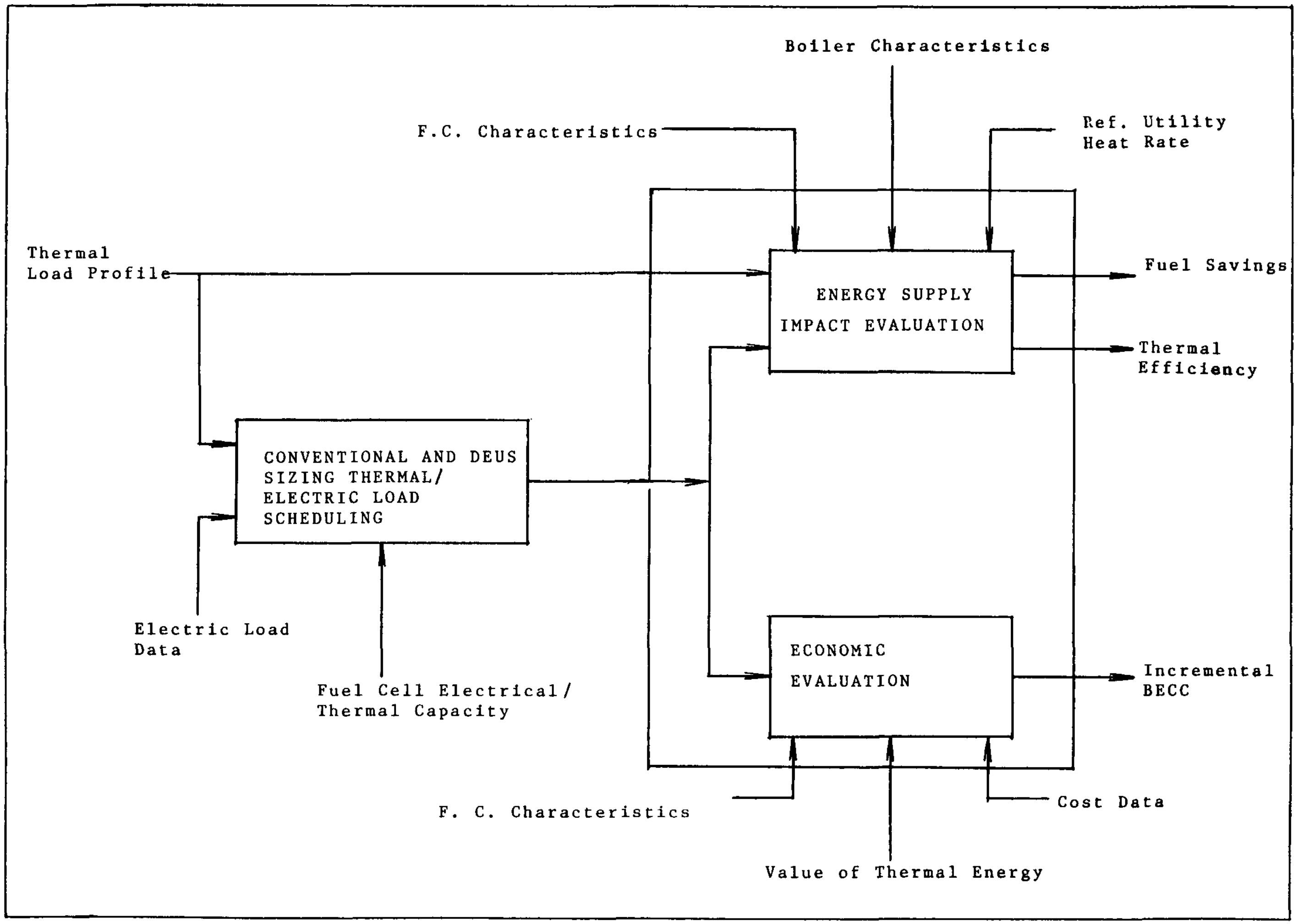


Figure 5-2. Overview of Evaluation Procedure.

Table 5-13

VALUE OF THERMAL ENERGY IN EACH INDUSTRY

INDUSTRY	NAME	SHIFTS	TOTAL THERMAL ENERGY VALUE $\$/10^6$ BTU			
			FUEL TYPE			
			COAL-1	COAL-2	OIL-1	OIL-2
2062	Cane Sugar Refining	2	1.87	2.81	3.60	4.40
2062	Cane Sugar Refining	3	1.91	2.85	3.64	4.44
2063	Beet Sugar	2	1.85	2.79	3.58	4.38
2063	Beet Sugar	3	1.89	2.83	3.62	4.42
2085	Distilled Liquors	2	1.99	2.93	3.72	4.52
2085	Distilled Liquors	3	2.04	2.98	3.77	4.57
2261	Finishing Plants Cotton	2	1.88	2.82	3.61	4.41
2261	Finishing Plants Cotton	3	1.91	2.85	3.64	4.44
2262	Finishing Plants Synthetic	2	1.91	2.85	3.64	4.44
2262	Finishing Plants Synthetic	3	1.93	2.87	3.66	4.46
2812	Alakalies and Chlonne	3	2.08	3.02	3.81	4.61
2824	Non-Cellulosie Fibers	2	1.84	2.78	3.57	4.37
2824	Non-Cellulosie Fibers	3	1.87	2.81	3.60	4.40
2865	Cyclic Crudes and Intermediates	3	1.95	2.89	3.68	4.48
2911	Petroleum Refining	3	1.97	2.91	3.70	4.50
2951	Paving Mixtures	3	2.76	3.70	4.49	5.29
2600	Paper and Pulp Mills	3	1.76	2.70	3.49	4.29

Assumptions-Fuel Prices: COAL - 1 = 1.25 $\$/10^6$Btu
COAL - 2 = 2.10 $\$/10^6$Btu
OIL - 1 = 2.50 $\$/10^6$Btu
OIL - 2 = 3.50 $\$/10^6$Btu

Boiler Costs : taken from
Boiler O&M Costs: 2.5% of Capital Costs
CCIF (Capital Compound Interest Factor) = 0.189

Operational Simulation

For each hour, the process heat requirements, the operating strategy, and the fuel cell characteristics decided the level of operation of the fuel cell and boiler. Energy flows and energy usefully employed were logged. Such logs were aggregated for annual operation to obtain the total energy balance for the entire DEUS plant, including

- fuel used in the fuel cell
- fuel used by boiler
- thermal energy supplied by fuel cell - temperature range 1
- thermal energy supplied by fuel cell - temperature range 2
- electricity produced
- thermal energy supplied by boiler

Economic Evaluation

The equations used for calculating the incremental breakeven capital costs (ΔBECC) were described in Section 3. Figure 5-3 illustrates the calculation process used. First the credits from the sale of thermal energy were calculated using the specified value of thermal energy and the amount of thermal energy provided. The net credits to the DEUS plant were then calculated by subtracting the electric generation penalties, if any, from the thermal credits. The penalty costs were calculated assuming incremental energy costs of 30.4 mills/kWh for on-peak costs of electricity generation and 21.3 mills/kWh for off-peak generation.

Incremental production costs for the DEUS plant were calculated based on fuel usage and O&M costs. The ΔBECC values were then calculated using Equation 3-1.

Energy Supply Impact Evaluation

All energy supply comparisons were based on an assumed parity in electrical and thermal production by the DEUS plant and the conventional alternative. For the conventional system, thermal energy was assumed to be produced by a boiler with an efficiency of approximately 83 percent. In those cases where the electrical production of the DEUS plant exceeded that of the conventional fuel cell, the conventional system was charged with the fuel required to produce the deficit at the reference utility system heat rate. On the other hand, when the

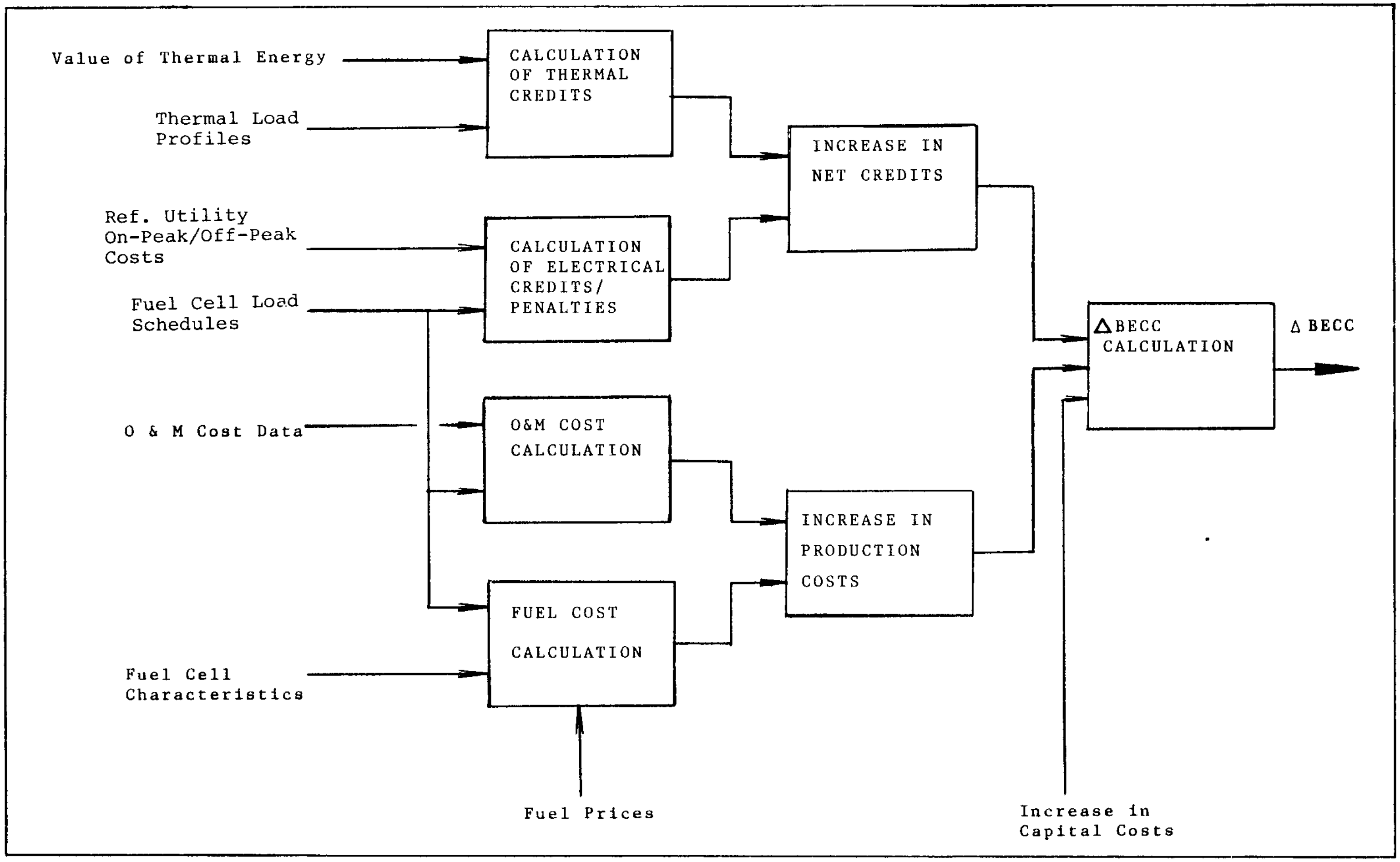


Figure 5-3. Illustration of Economic Evaluation Procedure.

electrical production of the conventional fuel cell exceeded that of the DEUS plant, the DEUS incurred a similar charge. Figure 5-4 illustrates these calculations. Both on-peak and off-peak electrical production were calculated for each system to allow a determination of the types of utility generation displaced (or required) by DEUS deviations from economic dispatch operation.

DISCUSSION OF RESULTS

As indicated previously, a large number of analyses were performed for the different industries for different plant designs, operating strategies and data values. A complete presentation of these results, including all load profiles, operating schedules, and input data would be overwhelming, confusing and possibly counterproductive. Instead, this section provides a comprehensive summary of the most interesting and pertinent results including

- detailed discussion of the analysis and results for one industry
- comparison and discussion of economic and energy supply results for the economic dispatch and thermal dispatch options for all industries.
- an overview and summary of the results for other evaluations
- results of the sensitivity analyses

Illustration of Calculations

Table 5-14 shows some of the results of the calculation procedure for SIC 2062. For an operating day, the fuel cell is operated at a fraction dictated by the relevant operating strategy. Its thermal outputs are noted from the fuel cell characteristics. Plant process heat requirements are satisfied by the fuel cell, and the remainder (if any) by the boiler. Fuel requirements and electricity produced are noted. Electricity production deviations from economic dispatch are noted. The operation is aggregated to 24 hours.

A similar procedure is carried out for the typical non-operating dav. The results are again aggregated to all operating and all non-operating days, and the annual operation results are obtained. As shown in Table 5-14, thermal energy from the boiler and fuel cell, and electricity and fuel consumption values at peak and off-peak times, are noted. Unit costs and credits are indicated. Using these values, the final

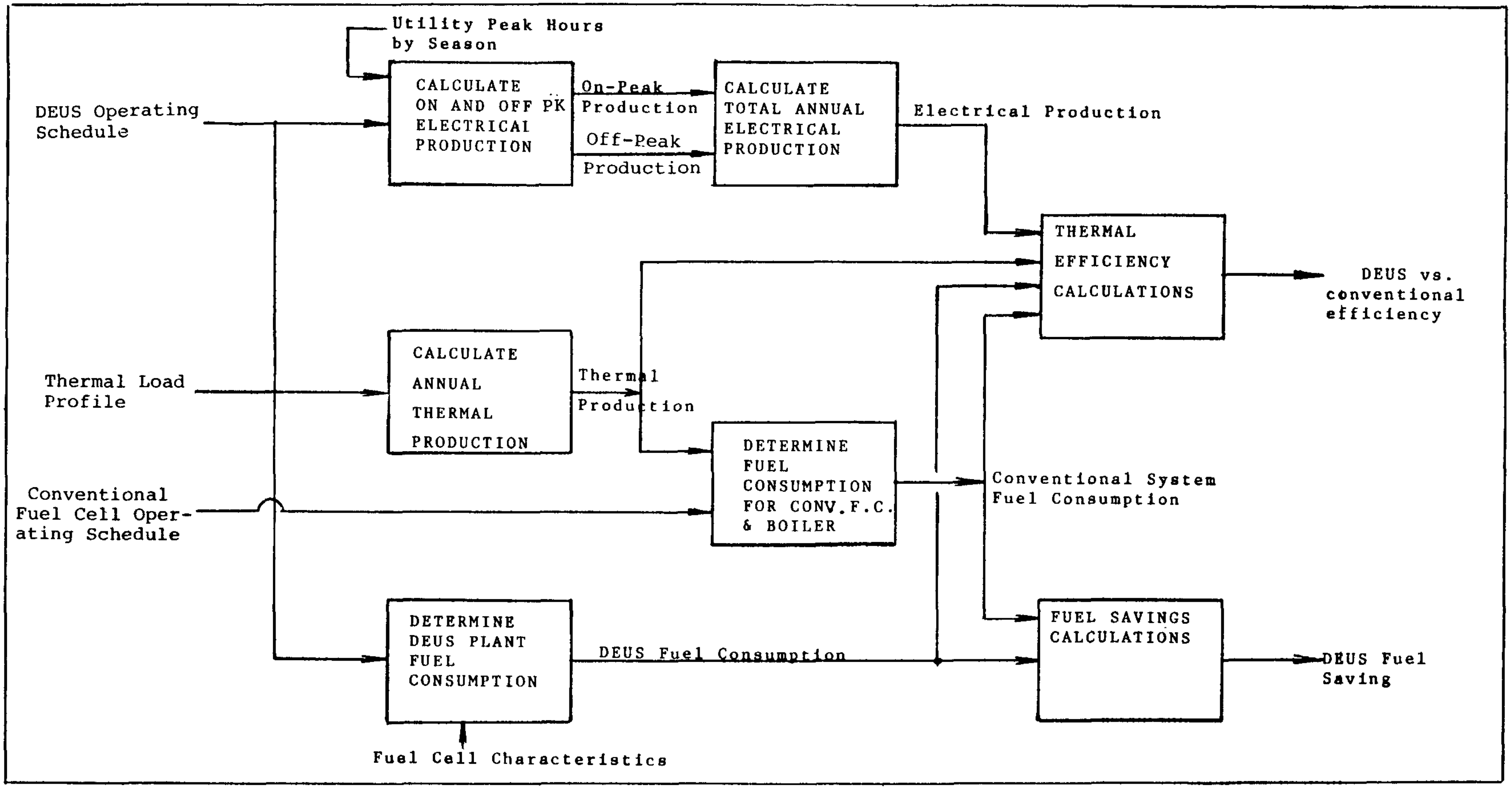


Figure 5-4. Illustration of Energy Supply Impact Evaluation.

Table 5-14

ILLUSTRATIVE RESULTS OF PLANT AND FUEL CELL PERFORMANCE LEADING UP TO ECONOMIC RESULTS

DISCRIPTION OF ITEM	OPERATING STRATEGY	
	Economic Dispatch	Thermal Load Following
Design Basis	Peak Process Heat Requirements in the Low Temperature Range	
Fuel Cell Size (MW)	13.5	13.5
Boiler Size (10^6Btu/hr)	260	228
Boiler Cost (1000$)	4546	4161
Thermal Energy from Fuel Cell (10^9 Btu)	279	318
Thermal Energy from Boiler (10^8 Btu)	1454	1415
Annual Fuel Cell Fuel Used(10^8Btu)	725	769
Annual Boiler Fuel Used (10^8 Btu)	1752	1705
Annual Electricity to Grid (million kWh)	79	84
Fuel Cell Fuel Cost ($/$10^6$ Btu)	2.45	2.45
Boiler Fuel Cost ($/$10^6$ Btu)	2.45	2.45
Value of Thermal Energy to Industry ($/$10^6$ Btu)	3.60	3.60
Marginal Cost of Electricity to Utility at Peak (mills/kWh)	30.7	30.4
Marginal Cost of Electricity to Utility at Off-peak (mills/kWh)	21.6	21.6
O&M Costs (mills/kWh)	2.85	2.85
Efficiency of DEUS System	0.81	0.82
Penalty Cost (1000$/yr)	0	99
Thermal Credits (1000$/yr) to Fuel Cell	1004	1145
Costs to Fuel Cell (1000$/yr)	0	99
Net Capital Credit to Fuel Cell (1000$/yr)	1004	1046
Increase in Breakeven Capital Cost due to DEUS Operating ($/kW)	393	410

credits and costs are calculated. Penalty costs are determined using the deviations in production and associated costs. The thermal performance is indicated by the efficiency. DEUS operation credit is obtained, and ΔBECC is determined.

Baseline Results

The "baseline" cases are the economic dispatch and thermal load following operating strategies for a fuel cell and supplementary boiler sized to satisfy thermal requirements in both the low (<212°F) and high (212-350°F) ranges. For these baseline analyses the Type I - phosphoric acid fuel cell, Configuration B, was used. A summary of the economic results and energy supply implications for the baseline cases is given below.

Economic Results. Tables 5-15 and 5-16 show the Incremental Breakeven Capital Costs (ΔBECC) for the two different sets of designs. All of the ΔBECC values are positive and greater than the cost of heat recovery modifications for Configuration B. Some of the values are quite high, ranging well over $300/kW. For the fuel cells designed to satisfy process heat requirements in the low temperature range, operation in the thermal load following mode generally increases ΔBECC. However, for the fuel cells designed to meet higher temperature (212-350°F) process heat requirements, the economic dispatch strategy appears consistently better, from an economic viewpoint, than thermal load following.

As pointed out earlier, in some industries, such as petroleum refining (SIC 2911) and paper and pulp mills (SIC 2600), there may be a significant amount of waste heat available from high temperature processes. Such waste heat could be recovered and utilized for satisfying the thermal energy needs in the less than 212°F and possibly also in the 212°- 350°F ranges. An evaluation of the technical feasibility and cost of waste heat recovery was beyond the scope of this effort. There is considerable current research underway to investigate opportunities and costs of industrial waste heat utilization. If reliable data on waste heat utilization were available, DEUS fuel cell economics could be reevaluated using a value of thermal energy equal to the cost of recovering waste heat. As shown later in the sensitivity analysis, the ΔBECC values are very sensitive to the value of thermal energy.

Table 5-15

INCREMENTAL BREAKEVEN CAPITAL COST FOR DEUS FUEL CELLS IN SELECTED INDUSTRIES

(Fuel cells designed to satisfy process heat requirements for temperature range <212°F)

INDUSTRY		FUEL CELL Size (MW)	ΔBECC ($/kW)	
SIC	Name		Economic Dispatch	Thermal Load Following
2062	Cane Sugar	18.0	302	271
2063	Beet Sugar	13.5	344	380
2085	Distilled Liquors	9.0	232	145
2261	Finishing Plants Cotton	18.0	340	398
2262	Finishing Plants Synthetic	27.0	301	317
2600	Paper and Pulp Mills	18.0	367	403
2824	Non-cellulosic Fibers	90.0	244	267
2911	Petroleum Refining	13.5	407	487

Table 5-16

INCREMENTAL BREAKEVEN CAPITAL COST FOR DEUS FUEL CELLS IN SELECTED INDUSTRIES
(Fuel Cell sizes designed to satisfy process heat requirements in temperature range 212-350°F)

SIC	INDUSTRY Name	FUEL CELL SIZE (MW)	ΔBECC ($/kW)	
			Economic Dispatch	Thermal Load Following
2062	Cane Sugar Refining	283.5	83	33
2063+	Beet Sugar	166.5	94	44
2085	Distilled Liquors	103.5	72	17
2261	Finishing Plant Cotton	76.5	155	147
2262	Finishing Plants Synthetic	40.5	238	227
2600	Paper and Pulp Mills	180.0	120	82
2812	Alkalies and Chlorine	612.0	71	23
2824	Non-cellulosic Fibers	4.5	374	84
2865	Cyclic Crudes and Intermediates	103.5	75	30
2911*	Petroleum Refining	49.5	207	170
2951	Paving Mixtures	697.5	72	41

But it appears that DEUS fuel cells can be economically viable even at thermal energy values as low as $1.50 to $2.00 per million Btu. If the cost of waste heat recovery exceeds this value, DEUS fuel cells can be economically attractive even in industries with significant waste heat utilization potential.

Energy Supply Results. Summaries of the energy efficiencies of the DEUS fuel cells and conventional fuel cells are shown in Tables 5-17 and 5-18. In all cases, the efficiency of the DEUS plant is higher than that of the conventional plant.

In the economic dispatch strategy, all the thermal energy supplied by the fuel cell results in a savings of boiler fuel with no change in the amount of fuel required from the fuel cell. The corresponding boiler fuel savings are indicated in Tables 5-19 and 5-20. These amount to annual savings of from 126 billion Btu to 1.4 trillion Btu for the designs based on meeting peak requirements below 212^{o}F. For the designs based on meeting peak 212-350^{o}F requirements, the energy savings range from 106 billion Btu to 2.6 trillion Btu.

In the thermal load following operating strategy, the DEUS fuel cell generally results in greater total energy savings than in the economic dispatch mode. However,some fuel displacement also takes place because the fuel cell may be producing electricity during off-peak hours thus displacing baseload coal or nuclear fuel with petroleum based fuels. In calculating fuel savings, therefore, it is important to note whether the fuel cell is displacing base load electricity production or peak-load electricity production. Any displacement of base load production will have implications in fuel displacement, namely, increased liquid fuel consumption for a saving of nuclear or coal. Similarly, the industry characteristics would show whether the boiler fuel saved is coal or oil. In order to assist in such inferences and assessment, fuel displacements in the thermal load following mode are compared to economic dispatch in Table 5-21.

Table 5-17

EFFICIENCIES OF THE CONVENTIONAL AND DEUS OPERATION OF FUEL CELLS
(Fuel cells sized for peak requirements in temperature range $<212^{\circ}F$)

SIC CODE	INDUSTRY NAME	FUEL CELL SIZE (MW)	Efficiency of Conventional Fuel Cell and Boiler	Efficiency of DEUS Fuel Cell and Supplementary Boiler
2062	Cane Sugar Refining	18.0	0.68	0.77
2063	Beet Sugar	13.5	0.66	0.78
2085	Distilled Liquors	9.0	0.62	0.71
2261	Finishing Plants Cotton	18.0	0.59	0.74
2262	Finishing Plants Synthetic	27.0	0.53	0.69
2600	Paper and Pulp Mills	18.0	0.70	0.80
2824	Non-cellulosic Fibers	90.0	0.50	0.63
2911	Petroleum Refining	13.5	0.80	0.83

Table 5-18

EFFICIENCIES OF THE CONVENTIONAL AND DEUS OPERATION OF FUEL CELL
(Fuel cells sized for peak requirements in temperature range 212-350°F)

SIC CODE	INDUSTRY NAME	FUEL CELL SIZE (MW)	EFFICIENCY OF CONVENTIONAL FUEL CELL AND BOILER	EFFICIENCY OF DEUS FUEL CELL AND SUPPLEMENTARY BOILER
2062	Cane Sugar Refinery	283.5	0.43	0.46
2063	Beet Sugar	166.5	0.43	0.47
2085	Distilled Liquors	103.5	0.41	0.45
2261	Finishing Plants Cotton	76.5	0.45	0.53
2262	Finishing Plants Synthetic	40.5	0.49	0.62
2600	Paper and Pulp Mills	180.0	0.46	0.52
2812	Alkalies and Chlorine	612.0	0.42	0.45
2824	Non Cellulosic Fibers	4.5	0.78	0.82
2865	Cyclic Crudes and Inter-	103.5	0.42	0.45
2911	Petroleum Refining	49.5	0.74	0.78
2951	Paving Mixtures	697.5	0.40	0.43

Table 5-19

BOILER FUEL SAVED DUE TO DEUS OPERATION OF FUEL CELL
(Fuel cell sized to peak requirements in temperature range <212°F)

SIC CODE	INDUSTRY NAME	FUEL CELL SIZE (MW)	BOILER FUEL SAVED (10^9 Btu/yr)
2062	Cane Sugar Refining	18.0	340
2063	Beet Sugar	13.5	292
2085	Distilled Liquors	9.0	126
2261	Finishing Plants Cotton	18.0	383
2262	Finishing Plants Synthetic	27.0	507
2600	Paper and Pulp Mills	18.0	431
2824	Non Cellulosic Fibers	90	1387
2911	Petroleum Refining	13.5	338

Table 5-20

BOILER FUEL SAVED DUE TO DEUS OPERATION OF FUEL CELL

(Fuel cell sized to peak requirements in temperature range 212-350^{O}F)

SIC CODE	INDUSTRY NAME	FUEL CELL SIZE (MW)	BOILER FUEL SAVED (10^9 Btu/yr)
2062	Cane Sugar Refining	283.5	1476
2063	Beet Sugar	166.5	985
2085	Distilled Liquors	103.5	451
2261	Finishing Plants Cotton	76.5	740
2262	Finishing Plants Synthetic	40.5	599
2600	Paper and Pulp Mills	180.0	1415
2812	Alkalies and Chlorine	612.0	2587
2824	Non Cellulosic Fibers	4.5	106
2865	Cyclic Crudes and Intermediates	103.5	479
2911	Petroleum Refining	49.5	632
2951	Paving Mixtures	697.5	2540

Plants are of large size and of three shift operation except SIC 2063 (medium size) and SIC 2951 (one shift)

Table 5-21

FUEL DISPLACEMENT BETWEEN THERMAL FOLLOWING MODE AND ECONOMIC DISPATCH

SIC	Industry Name	Fuel Cell Size (MW)	Additional Electricity Produced Th following - Eco dispatch		Additional Fuel Cell Fuel Th following - Eco dispatch		Additional Boiler Fuel Used (10^9 Btu)
			Peak (10^6 kw hrs)	Off Peak 10^6 (kw hrs)	Peak (10^9 Btu)	Off Peak (10^9 Btu)	
2062	Cane Sugar Refining	18.0	-37	23	-352	214	43
2063	Beet Sugar	13.5	-19	24	-175	232	96
2085	Distilled Liquors	9.0	-26	5	-249	48	- 7
2261	Finishing Plants Cotton	18.0	-23	34	-217	323	151
2262	Finishing Plants Synthetic	27.0	-46	42	-439	393	145
2600	Paper and Pulp Mills	18.0	-20	37	-199	339	120
2812	Alkalies and Chlorine	612.0	-807	1146	-7617	1081	1081
2824	Non Cellulosic Fibers	90.0	-128	161	-1208	1518	568
2865	Cyclic Crudes and Intermediates	103.5	-110	215	-1041	2027	203
2911	Petroleum Refining	13.5	-10	31	-104	291	125
2951	Paving Mixtures	697.5	-933	0	-8838	0	0

SENSITIVITY ANALYSIS

Incremental Breakeven Capital Costs (ΔBECC) values are sensitive to the value of thermal energy, the cost of fuel cell fuel and the marginal cost of electricity. The latter two costs affect the penalty costs and since the penalty costs are zero in the economic dispatch strategy, only the value of thermal energy affects the Incremental Breakeven Capital Cost (ΔBECC) value for the economic dispatch case.

In order to investigate the sensitivity, for the industry SIC 2062, (cane sugar refining), the value of thermal energy was varied from a mean value of $3.64 per million Btu by ± 10% and ± 5%. The results are shown in Table 5-22. For this typical case the Incremental Breakeven Capital Cost (ΔBECC) values vary by the same percentage points for economic dispatch, while the variation is slightly greater for the thermal following mode.

However, it should be noted that this result cannot be generalized to all industries because the sensitivity depends on the size of the fuel cell and the fraction of its output effectively utilized.

Illustrative results for the sensitivity of ΔBECC to the cost of fuel and marginal cost of electricity are presented in Tables 5-23 and 5-24. Again, it should be emphasized that the sensitivity values are not uniform over all industries and over all options and operating strategies.

The cost of fuel and the incremental costs of electricity affect the penalty costs. In a given case, penalty costs depend on the deviation of the fuel cell operation from economic dispatch. The penalty costs vary by about $30 per kW, and affect the incremental breakeven capital cost to that extent.

Table 5-22

SENSITIVITY OF INCREMENTAL BREAKEVEN CAPITAL COST (ΔBECC) TO THE VALUE OF THERMAL ENERGY

(SIC 2062 Cane Sugar Refining)

Percent Variation	-10%	-5%	BASE	+5%	+10%
Thermal Value ($\$/10^6$ Btu)	3.28	3.46	3.64	3.82	4.00
<u>ECONOMIC DISPATCH</u> ΔBECC ($/kW) *	272	287	302	317	332
Variation *	-10%	-5%	0	+5%	+10%
<u>THERMAL FOLLOWING</u> ΔBECC ($/kW)	236	253	271	287	303
Variation	-13%	-17%	0	+6%	+12%

- 18 MW, Type I Fuel Cell sized to peak requirements <212°F
- Heat Recovery, Configuration B

Table 5-23

SENSITIVITY OF INCREMENTAL BREAKEVEN CAPITAL COSTS TO FUEL CELL FUEL PRICE (SIC 2062 Cane Sugar Refining)

Percent Variation	-10%	BASE	+10%
Fuel Price ($/10^6 Btu)	2.21	2.45	2.70
Δ BECC ($/kW)	262	271	282
Percent variation	-3%	0	+4%

Fuel cell sized to peak process heat requirements in the low temperature range

Fuel cell size = 18.0 MW

Value of thermal energy = 3.64 ($/10^6 Btu)

Table 5-24

SENSITIVITY OF INCREMENTAL BREAKEVEN CAPITAL COST TO MARGINAL COST OF ELECTRICITY (SIC 2062 Cane Sugar Refining)

Data Item	Per Cent Variation		
Percent Variation	-10%	BASE	+10%
Electricity cost at peak ($/kW hr)	0.0274	0.0304	0.0334
Electricity cost at off-peak ($/kW hr)	0.0194	0.0216	0.0238
Δ BECC ($/kW)	289	271	254
Percent Variation	+7%	0	-6%

Fuel cell sized to peak process heat requirements in the low temperature range <212°F.

Value of thermal energy = 3.64 ($/10^6 Btu)

Fuel cell fuel cost = 2.45 ($/10^6 Btu)

INVESTIGATION OF ALTERNATIVE OPTIONS AND ASSUMPTIONS

Sizing on Average Requirements

When the DEUS fuel cell is sized to average requirements rather than peak requirements, the ΔBECC values are consistently better as seen from Table 5-25. The average requirement criterion generally reduces the fuel cell size and improves the Incremental Breakeven Capital Cost (ΔBECC) values considerably, because a higher proportion of fuel cell thermal energy is utilized.

Plant Operation on Two Shifts

Where plants can operate either on three shifts or two shifts, the two shift operation gives higher ΔBECC values, because it is closer to the utility load profile. The results are illustrated in Table 5-26.

Thermal Storage

Thermal storage improves energy utilization efficiency. But the economics depend on storage costs versus credits due to energy savings. Storage decreases the fuel cell size and the boiler size, and allows the operation of the fuel cell at full rated capacity during peak hours, and stores the thermal energy for off-peak requirements. An inspection of the costs of storage units for industrial applications reveals that the costs are very high and relative to the savings that result. This is particularly true for the thermal profiles employed in this analysis.

Heat Pump

The use of an industrial heat pump could upgrade the low quality heat for use at 350°F. Figure 5-5 shows a schematic arrangement of a fuel cell incorporating an industrial heat pump. It is assumed that a heat pump would have a Coefficient of Performance (COP) of 1.5. Industries in SIC groups 2063,2261, 2600, and 2911 may take advantage of a heat pump, because the proportion of thermal energy required in the 212-350°F range is higher in these industries than the proportion available from the fuel cell. The heat pump can take (x) Btu of low temperature heat and convert it to (3x) Btu of high temperature heat utilizing 2x Btu of electricity. At this COP the heat pump is not economical, since it is using electricity valued (even at off-peak) at 21.4 mills/kWh or over $6.00 per million Btu to produce 1.5 million Btu of energy (212-350°F) valued at about $3.60 per

Table 5-25

EFFECT OF SIZING THE DEUS FUEL CELL TO MEET AVERAGE THERMAL REQUIREMENTS

INDUSTRY		ΔBECC ($/kW) Fuel Cell Sizing Based On Process Heat Requirements			
		PEAK		AVERAGE	
SIC CODE	NAME	SIZE (MW)	ΔBECC ($/kW)	SIZE (MW)	ΔBECC ($/kW)
2063	Beet Sugar Refining	13.5	388	9.0	419
2262	Finishing Plants, Synthetic	22.5	404	18.0	429
2824	Noncellulosic Fibers	81.0	313	58.5	342

Fuels cells sized to process heat requirements <212°F
Fuel cell operation: economic dispatch

Table 5-26

EFFECT OF NUMBER OF SHIFTS OF PLANT OPERATION ON INCREMENTAL BREAKEVEN CAPITAL COST

Industry		Plant Operation			
		3 Shifts		2 Shifts	
SIC Code	Name	Fuel Cell Size (MW)	ΔBECC ($/Kw)	Fuel Cell Size (MW)	ΔBECC ($/Kw)
2063 *	Beet sugar refining	13.5	344	13.5	388
2262 *	Finishing plants, synthetic	27.0	301	22.5	404
2824 *	Noncellulosic fibers	90.0	244	81.0	313
2062 †	Cane sugar refining	283.5	83	261.0	101
2085 †	Distilled liquors	9.0	72	4.5	88

* Fuel cell sized on peak thermal requirements in the low temperature range

† Fuel cell sized on peak thermal requirements in the high temperature range

Operating strategy is economic dispatch
Fuel cell fuel price = 2.45 $/$10^6$ Btu

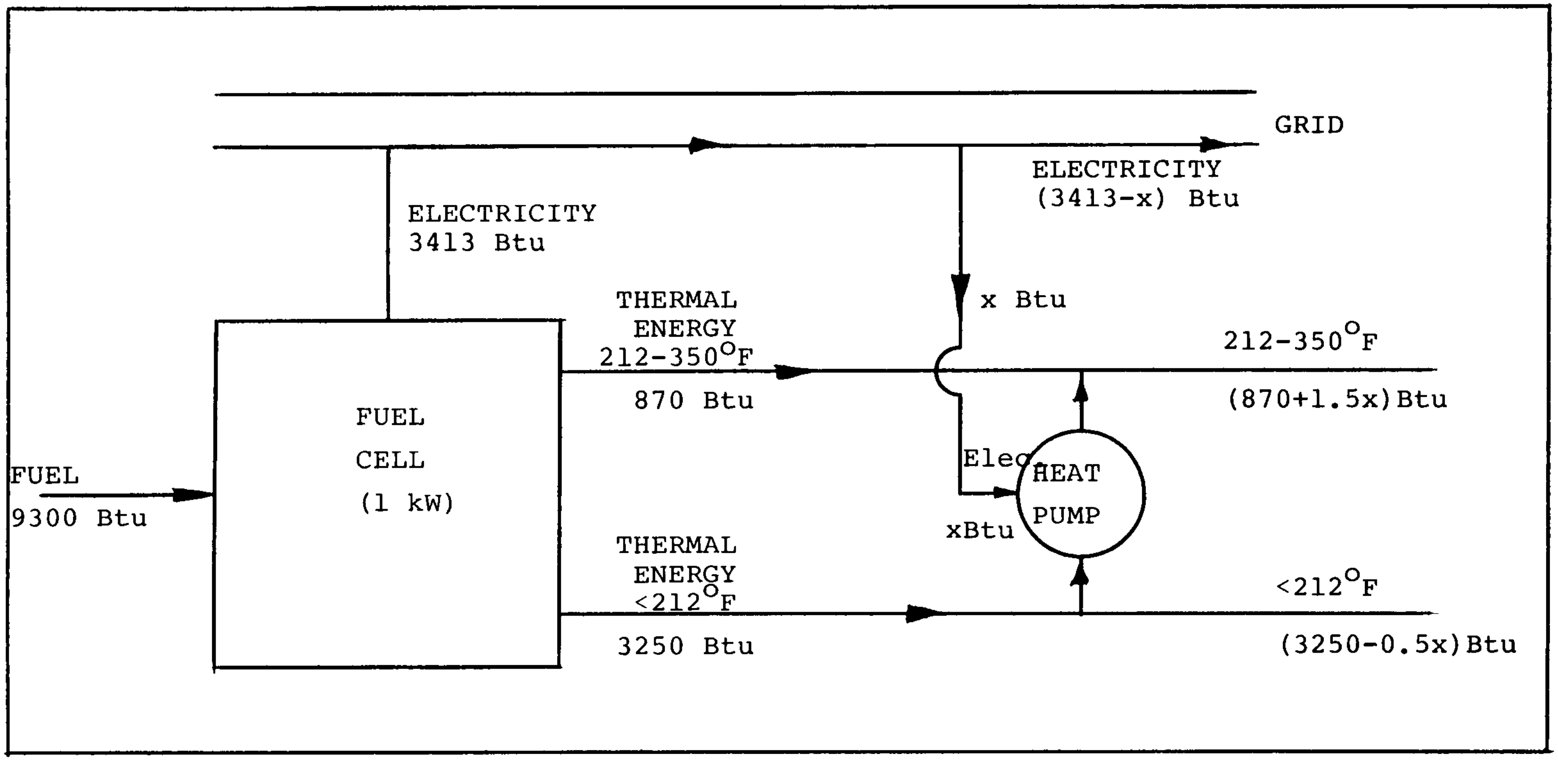


Figure 5-5. Fuel Cell with Industrial Heat Pump.

million Btu (or a total value of \$5.40 per million Btu). Therefore, the use of a heat pump would not be economically feasible unless

- the value of off-peak electricity were lower,
- the value of thermal energy were higher, or
- heat pumps with a higher COP were developed

Effect of Fuel Cell Modification

For the Type I - phosphoric acid fuel cell, Configuration C can provide additional higher temperature thermal energy by modifying the fuel cell thermal management system as described in Section 2. An analysis of the potential benefits of this modification was performed. The comparative results for ΔBECC for Configuration C, Option II versus Configuration B are shown in Table 5-27. In all cases except SIC 2829, in which there are no thermal requirements in the 212-350°F range, Configuration C, Option II achieves a higher ΔBECC than Configuration B, and the difference is generally higher than the additional capital cost of the modification to the fuel cell.

Effect of Variation of Value of Thermal Energy

In certain locations and/or in certain geographic areas, it is possible that all process heat requirements are met by boilers fired with coal (or some other inexpensive fuel). In such cases, the value of thermal energy would be smaller. A range of fuel cost scenarios were examined to analyze the sensitivity of ΔBECC to thermal value. The results are graphically presented in Figure 5-6. For the economic dispatch strategy, the Incremental Breakeven Capital Cost varies linearly with the value of thermal energy.

Effects of Higher Fuel Prices

For a fuel price of \$3.50 instead of \$2.50 per million Btu the ΔBECC values increase considerably, since the value of thermal energy (which is assumed to be equal to the cost of conventional methods of supplying thermal energy) provides greater credits. For SIC 2062, Cane Sugar Refining, under economic dispatch the Incremental Breakeven Capital Cost increases to 402 \$/kW, and for the thermal dispatch operating startegy the value is 477 \$/kW. It may, however, be noted that the above values are only the incremental values over conventional fuel cell Breakeven Capital Costs. These conventional

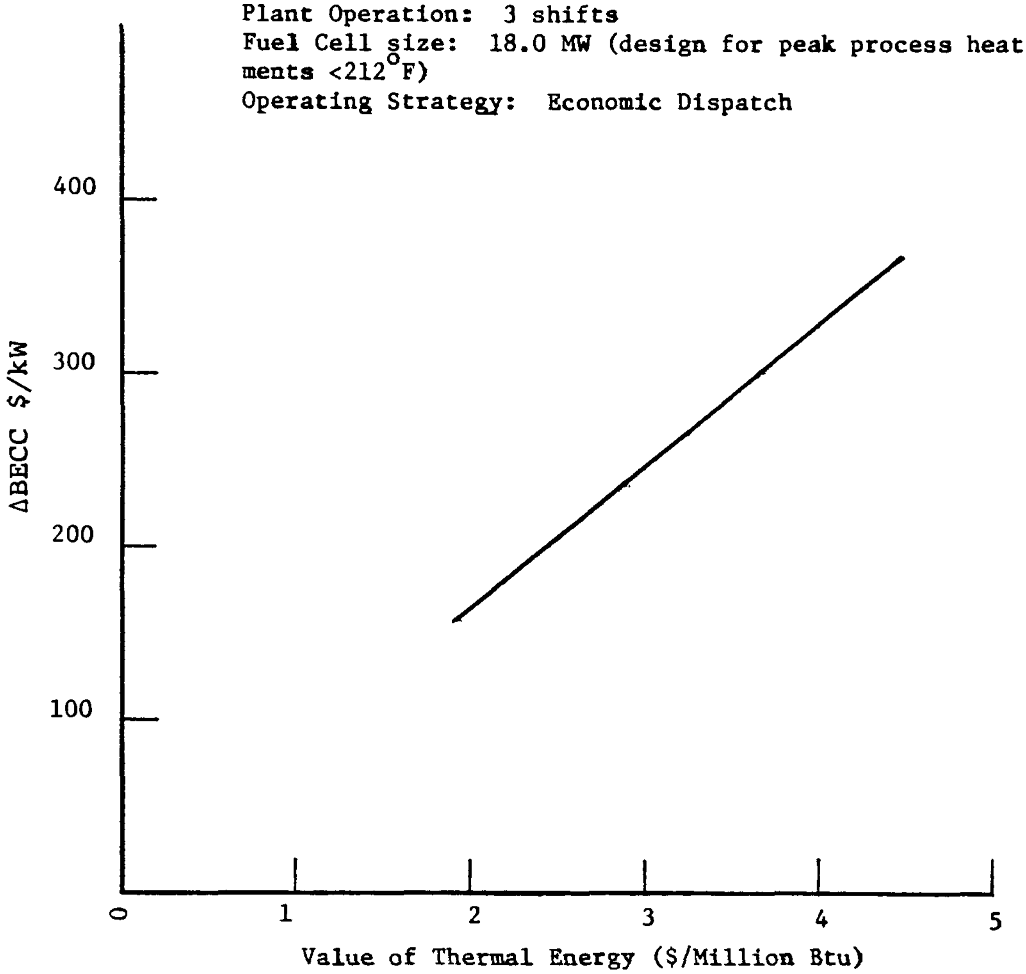
Table 5-27

EFFECT OF FUEL CELL MODIFICATION TO OBTAIN MORE HEAT IN THE HIGHER TEMPERATURE RANGE

(Configuration C,Option II)

SIC CODE	NAME	Configuration B		Configuration C Option II	
		Fuel Cell Size (MW)	ΔBECC ($kW)	Fuel Cell Size (MW)	ΔBECC ($/kW)
2062	Cane Sugar Refining	18.0	302	13.5	387
2063	Beet Sugar	13.5	344	13.5	365
2085	Distilled Liquors	9.0	232	9.0	253
2261	Finishing Plants, Cotton	18.0	340	18.0	356
2262	Finishing Plants, Synthetic	27.0	301	22.5	355
2600	Paper and Pulp Mills	18.0	367	18.0	388
2824	Non Cellulosic Fibers	90.0	244	85.5	239
2911	Petroleum Refining	13.5	407	13.5	427

Fuel Cells sized to process heat requirements $<212^{\circ}$F.



Industry: SIC 2062 Cane Sugar Refining
Plant Operation: 3 shifts
Fuel Cell size: 18.0 MW (design for peak process heat requirements <212°F)
Operating Strategy: Economic Dispatch

Figure 5-6. Effect of Variation of the Value of Thermal Energy on the Incremental Breakeven Capital Cost.

fuel cell Breakeven Capital Costs will not be expected to remain unchanged with the higher fuel costs, but will presumably decrease quite considerably.

EVALUATION OF TYPE II - MOLTEN CARBONATE FUEL CELL

Section 2 described the characteristics of Type II - molten carbonate fuel cells. These fuel cells have a lower heat rate but do provide some heat in the temperature range 1035-1060^{O}F. It is expected that these fuel cells could be advantageously employed in industrial plants with process heat requirements up to 1000^{O}F. However, the amount of 1035-1060^{O}F heat available from a Type II - molten carbonate fuel cell represents only about 6 percent of all available reject heat. Thus, only applications with relatively small high temperature heat requirements will benefit significantly from the availability of this heat.

If low and high temperature heat streams from these Type II fuel cells are mixed, a significant amount of reject heat in the 350 to 500^{O}F range could be produced. Applications that require process heat in this temperature range may benefit from the implementation of Type II DEUS fuel cells, since Type I - phosphoric and fuel cells do not produce reject heat at temperatures above 350^{O}F.

SIC 2062, Cane Sugar Refining, was analyzed for a Type II - molten carbonate,DEUS, fuel cell, and the results obtained are presented in Table 5-28. Three fuel cell sizes were examined which satisfy the thermal requirements in the three temperature ranges described previously. For these fuel cells, excellent energy utilization efficiency values were obtained. However, as the fuel cell size is increased, the Incremental Breakeven Capital Cost decreases, since the thermal energy usable in the industry plant does not increase in the same proportion as the fuel cell size. Incremental Breakeven Capital Costs of 113 to 302 $/kW were obtained (for the cases presented in Table 5-28). A comparison with Type I fuel cell DEUS results shows that the values obtained for the smaller fuel cells are the same with either type fuel cell, while for the larger sizes the Type II fuel cell has a small advantage over the Type I fuel cell.

Table 5-28

TYPE II FUEL CELL ANALYSIS AND RESULTS (Industrial Plant: SIC 2062 Cane Sugar Refining Large Plant - Three Shifts)

ITEM	FUEL CELL SIZES		
Fuel Cell Size (MW)	18	36	207
Size Design basis, temperature range	<212° F	550-1000°F	212-350°F
Required Supplementary Boiler Size (10^6 Btu/hr)	280	244	175
Strategy of Operation	Economic Dispatch	Economic Dispatch	Economic Dispatch
Annual Electricity Generated (10^6 kWh)	103	207	1,190
Value of Electricity Produced (1000$/yr)	2,984	5,970	34,346
Annual Fuel Cell Fuel Used (10^9 Btu)	786	1,572	5,670
Annual Thermal Energy Used From Fuel Cell (10^9 Btu)	283	419	1,217
Credit for Thermal Energy (1000$/yr)	1,030	1,525	4,430
ΔBECC ($kW)	302	224	113
Boiler Fuel Saved (10^9 Btu/yr)	341	505	1,466
(1000 bbl oil equiv./yr)	56	84	244
Efficiency of DEUS Plant	0.81	0.72	0.93
Proportion of process heat supplied by fuel cell %	17	27	71
Proportion of fuel cell thermal output gainfully used %	36	25	21

Fuel Cell fuel cost = $2.45\ \$/10^6$ Btu
Value of thermal energy = $3.64\ \$/10^6$ Btu
Marginal cost of electricity at peak : 0.0304 (\$/kWh)
at off-peak: 0.0216 (\$/kWh)

The results presented here are for only one industry plant with one fuel cell operating strategy and it is not appropriate to generalize them without a detailed investigation of the Type II fuel cell. However, it is clear from this example that the Type II fuel cell does not offer a significant economic advantage over the Type I in terms of thermal energy utilization potential.

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Section 6

UTILITY APPLICATIONS

SECTION SUMMARY

The utility sector provides a number of opportunities for the use of fuel cell reject heat with the attendant energy and economic advantages. The issues of ownership and grid connection are very simple in this case, since the utility is both supplier and consumer of the reject heat. Three applications of fuel cell dual energy use systems to central station steam power plants were selected for detailed evaluation, and typical data was developed for representative plants. DEUS fuel cell system operation in the economic dispatch and thermal load following modes were examined for each application. The major findings are summarized below:

- A fuel cell installation for air preheating is economically advantageous. A preliminary analysis showed an incremental breakeven capital cost ranging from $94/kW to $300/kW for intermediate and base load fossil units.
- There appears to be an economic advantage in installing fuel cells for feedwater heating applications. A large number of fuel cells are required as an alternate heat source for the bottom feedwater heater of a base load unit. Because of the space required and the thermal losses and costs involved for base load units, DEUS installations appear to be more attractive for intermediate load plants, which are somewhat smaller in size.
- The application of fuel cells for HVAC and auxiliary steam requirements appears to be feasible when coupled with either of the above applications.

This section describes the specific utility applications considered, the process of selecting those applications to be analyzed in detail, and the subsequent evaluation results. The major findings of the utility analysis are summarized.

IDENTIFICATION AND SCREENING OF APPLICATIONS

Various utility system requirements for thermal energy were considered as potential applications for fuel cell dual energy use systems. These applications include

- air preheat in a fossil-fired power plant
- use for feedwater heating in a steam power plant
- auxiliary steam for HVAC uses
- combined cycle power generation
- use of thermal energy in a Synthetic Natural Gas (SNG) plant or a Liquefied Natural Gas (LNG) terminal in a combination gas and electric utility
- stack gas reheat application
- coal supply heating (in winter)
- condensate pipe heating (in winter)

Preliminary calculations were made for each of these applications and their thermal requirements were determined. All applications were then screened to eliminate those for which

- quantity of thermal energy required is less than 4.5 MW
- quality of thermal energy required can not be produced by a fuel cell DEUS
- number of application opportunities is limited
- reliable data on the application is not available

The results of this screening process are summarized by application in Table 6-1. The specific applications selected for analysis are discussed below.

Thermal Requirements of Selected Applications

A steam electric plant, either fossil-fueled or nuclear, requires a number of in-house auxiliary thermal energy supplies for the purpose of more effective, economic operation. These supplies are generally provided by extracting steam at various stages. If such steam is supplied from another source, then steam extraction from the main plant will be either reduced or eliminated, and the plant operating efficiency and electric output would be increased accordingly. A number of these auxiliary thermal energy uses are described below.

Air Preheat. Preheating the inlet air to boilers increases the combustion efficiency. This is particularly significant during the winter season.

Table 6-1

SCREENING PROCESS AND RESULTS

	Application	Decision	Reasons
ACCEPTED	Air preheat	selected	large heating requirements; saving of steam
	Feed water heating	selected	large heating requirements; saving of steam
	Auxiliary steam, HVAC uses	selected as an add on to	small savings in steam
REJECTED	Combined cycles	rejected	low quality of steam available from fuel cell
	Thermal energy in SNG and LNG plants	rejected	limited number of applications
	Stack gas reheat	rejected	lack of reliable and sufficient data
	Coal supply heating	rejected	limited potential
	Condensate pipe heating	rejected	limited potential

Steam power plants require an inlet air temperature of 150°F. During spring and summer months this 150°F demand is more easily met. Ambient air temperature is less than the required temperature, and fuel cell waste heat has a potential use.

The ratio of combustion fuel to air is 1 lb of fuel to 12 lbs of air. Utilizing the sample 1000 megawatt power plant referenced from Table 2-11 of Reference (1), the calculated coal consumption is 720,000 lb per hour, and fuel oil consumption is 475,000 lb per hour. This computation assumes the calorific value of coal 13,000 Btu/lb and fuel oil is 20,000 Btu/lb. Thus,

$0.72\text{x}10^6$ lb/hr of coal requires $11.5\text{x}10^6$ lb/hr of air

and

$0.475\text{x}10^6$ lb/hr of fuel oil requires $7.6\text{x}10^6$ lb/hr of air.

Table 6-2 presents thermal requirements as a function of ambient air temperature.

Boiler Feedwater and Condensate Heating. The preheating of boiler feedwater would also increase the potential heat rate of a steam power plant due to lessening of required bleed steam.

The demands shown in Table 6-3 are based on an actual heat rate for an 1100 megawatt nuclear generating plant. The total required feedwater flow is about 32,000 gallons per minute. Table 6-3 is a heat balance with temperature transfer for the string of five (5) feedwater heaters. In addition, the table shows the heat of feedwater for the corresponding temperature range, and the resulting quantity of feedwater heat and the required steam quantity.

Plant Building HVAC and Auxiliary Steam Requirements. An existing 1000 megawatt power plant, installed within the PSE&G system has a HVAC requirement of 300 tons, or a maximum building load of $3.6\text{x}10^6$ Btu/hr. This load includes control room, offices, service area, and workmen's quarters. Table 6-4 shows these heat requirements.

Other auxiliary uses of steam are to maintain freeze protection for fuel oil tanks, fuel lines, and fuel preheating for combustion. The following demands are based on a million gallon oil tank capacity. Tank heaters require 220 lb/hr of steam; fuel oil heaters 230 lb/hr

Table 6-2

HEAT FROM FUEL CELL TO PREHEAT BOILER INTAKE AIR TO 150°F

OUTSIDE AMBIENT AIR (°F)	REQUIRED TEMPERATURE CHANGE (°F)	COAL UNIT HEAT REQUIRED TO HEAT INTAKE AIR (10^6 Btu/hr)	OIL UNIT HEAT REQUIRED TO HEAT (10^6 Btu/hr)
100	50	103.8	91.0
95	55	114.0	100.0
90	60	124.5	109.2
85	65	134.6	118.3
80	70	145.3	127.4
75	75	155.5	136.5
70	80	166.0	145.6
65	85	176.0	154.7
60	90	186.3	164.0
55	95	197.0	172.9
50	100	207.5	182.0
45	105	218.0	191.0
40	110	238.0	200.2
35	115	238.0	209.3
30	120	249.0	218.4
25	125	260.0	227.5
20	130	270.0	236.6
25	135	280.0	245.7
10	140	290.0	254.8
5	145	300.0	263.9
0	150	311.0	293.0

Table 6-3

HEAT SUPPLIED BY FUEL CELLS TO STAGED FEEDWATER HEATERS (Typical 1000 MW Unit Application)

Feedwater Heater		Heat Gained by Feedwater Heaters (Q_F) (10^6 Btu/hr)	Heat Required from Fuel Cells (Q_H) (10^6 Btu/hr)	Heater Efficiency (%) (Q_F/Q_H)x100
Number	ΔT (°F)			
1	76	1050	1080	97
2	36	500	570	87
3	51	710	780	91
4	53	760	830	92
5	59	860	950	91
Average	55	780	840	92

Table 6-4

HEAT REQUIREMENTS FROM FUEL CELLS FOR HVAC AND AUXILIARY STEAM REQUIREMENTS (For Typical 1000 MW Unit Applications)

System	Heat Requirement 10^6 Btu/hr
HVAC (Control Room, Offices Service Area, Misc.)	3.6
Heat Treatment for Fuel System	1.2
Total	4.8

of steam; pipe line steam tracing 180 lb/hr of steam; and the tank heat loss is 330 lb/hr of steam. Thus, approximately 1000 pounds per hour of 150 psia steam is required.

DEUS MATCHING/DECOUPLING OPTIONS

In the case of the utility applications, any portion of the thermal requirements may be supplied from the DEUS fuel cells, as the deficits can be met by the utility plant steam generating system. Hence, a number of fuel cell plant sizes are possible. Thermal storage could also be considered for such applications. However, since the thermal supply in utility power plant applications does not rely solely on the DEUS fuel cells, there would be little advantage in considering such storage. Therefore only the following two options were investigated.

- DEUS fuel cell supplying entire thermal requirement
- DEUS fuel cell and plant steam generating system supplying thermal requirement

Operating Strategies

In evaluating the selected steam power plant applications of DEUS fuel cells, the hourly operation of the fuel cell plant was assumed to be the same as that for the power plant it served.

Applications Analysis

Analysis Methodology. The basic model for the utility applications analysis is shown in Figure 6-1. The methodology comprises the following

- computation of thermal requirements in the utility power plant
- identification of fuel cell sizes and options, (the options are (1) fuel cell supplying entire needs, (2) fuel cell supplying partial needs
- computing the capital costs of changes to the DEUS
- determining the operating patterns, analyzing a representative week for each of the four seasons conjunctively with the two design options
- computing the costs associated with the fuel and O&M requirements for the operation of the DEUS fuel cell
- calculating the value of the electricity produced by the fuel cell based on the utility's replacement costs of capacity and energy

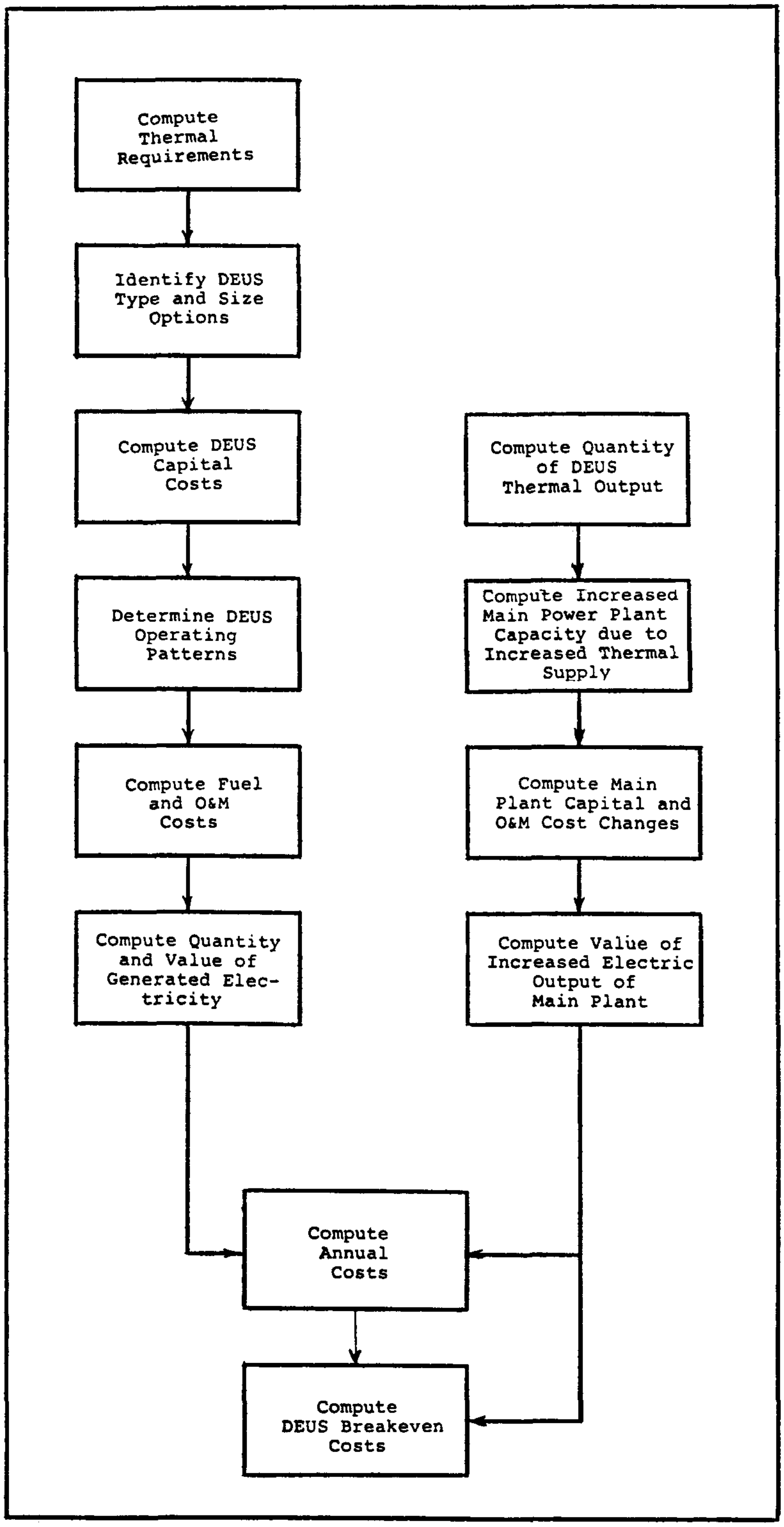

Figure 6-1. Analysis Methodology for Utility Applications.

- computing the DEUS thermal output
- using the DEUS thermal output to determine the increase in electrical energy produced by the specific power plant
- calculating the main plant capital and O&M cost changes due to the increased electrical energy generating capacity
- computing the value of the increased electrical energy generating capacity
- aggregating the annual credits and costs
- finally, computing the Incremental Breakeven Capital Costs due to DEUS fuel cells

Illustrative Application of Sizing

A 1000 MW coal fired power plant was considered as a typical application. Air and water preheat requirements of such a plant were calculated. Table 6-5 shows typical design sizes along with the relevant applications.

Table 6-5

DESIGN SIZES OF DEUS FUEL CELLS
FOR A 1000 MW COAL FIRED POWER PLANT

Application	Heat Required (1000 Btu/hr)	Fuel Cell Size (MW)
Air preheat	186	45
Feed water (bottom heater)	1080	396
Feed water (Top heater & bottom heater (partial)	542	198

Analysis of the Cycle with Heater Modification

Figure 6-2 shows a schematic diagram of a DEUS fuel cell integrated into a coal fired power plant thermal system. Air preheating is done partly by bleeding some steam from the turbine and partly by the fuel cell reject heat. The analysis involved the calculation of the bleed steam saved, the work it would produce in the turbine and how much it is worth in terms of the additional capacity it created and the electricity that is produced.

Figure 6-3 shows a schematic diagram of a DEUS fuel cell integrated into a coal fired power plant thermal system for boiler feedwater heating. Fuel cell reject heat is used to heat the feedwater. This releases the bleed steam for full expansion in the turbine, increasing both the plant electrical capacity and its electric energy production.

Economic Evaluation

Both the feedwater heating and the air preheating by DEUS fuel cell reject heat improve the plant performance by:

- increasing electrical output
- reducing fuel consumption

If the fuel used is kept constant, all the gains are seen in terms of increased electrical output. Conversely, if the electrical output is kept constant, fuel input is reduced. Either the electrical credit or the fuel cost saved or a fraction of each, whichever is applicable, is calculated and annual savings levelized over the life of the plant are determined to obtain the incremental breakeven capital costs. Table 6-6 shows the cost data for such evaluation.

DISCUSSION OF RESULTS

For the air preheat application a number of fuel cell DEUS plant additions are considered and results are reported in Table 6-7. An incremental breakeven capital cost of 300 $/Kw is obtained for the case of a 45 MW fuel cell power plant integrated with a base load, coal fired plant.

Table 6-8 shows the results for feedwater heaters. These modifications provide only modest (nearly 100 $/Kw) incremental breakeven capital costs.

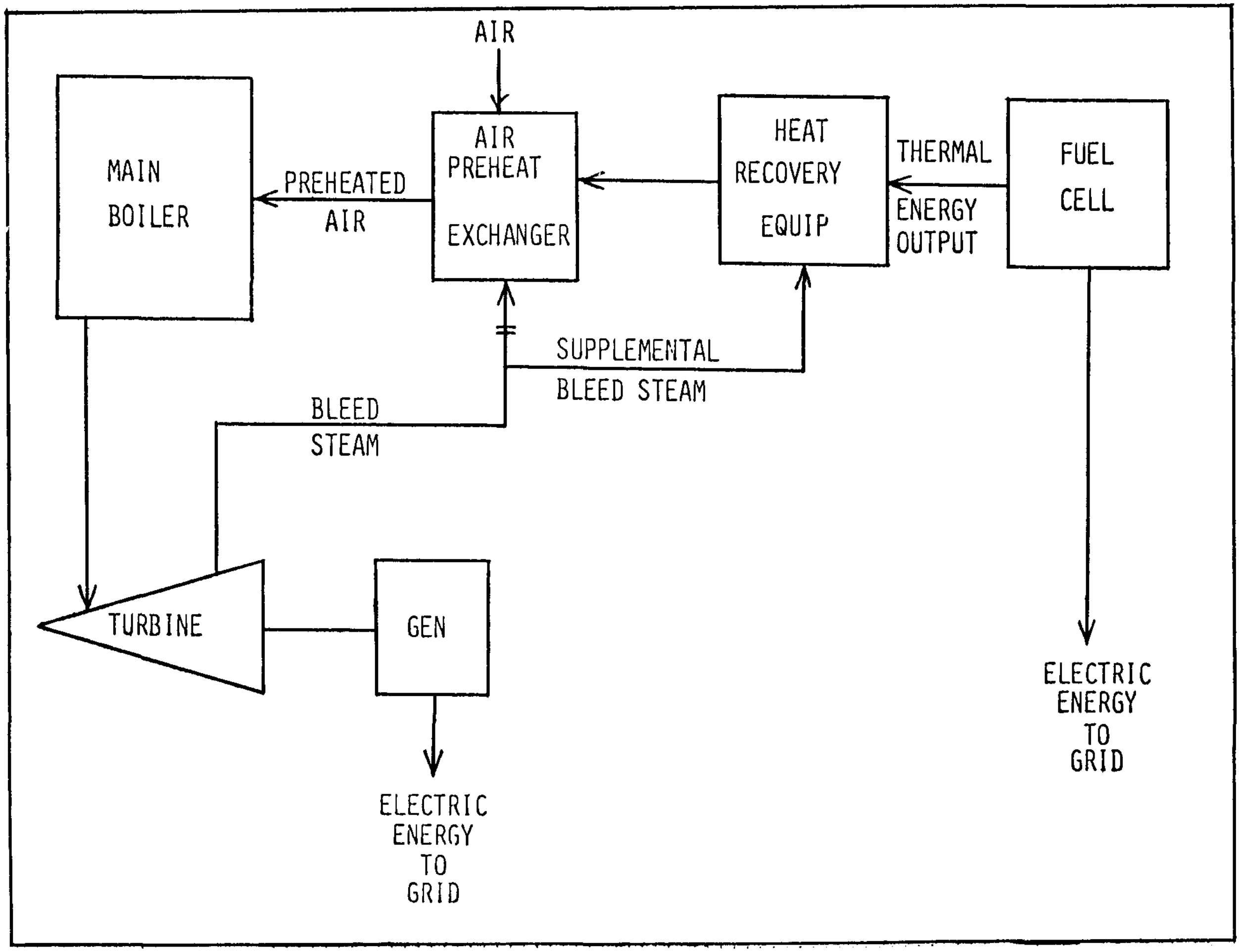

Figure 6-2. Utilization of Fuel Cell Reject Heat for Boiler Air Preheat Application.

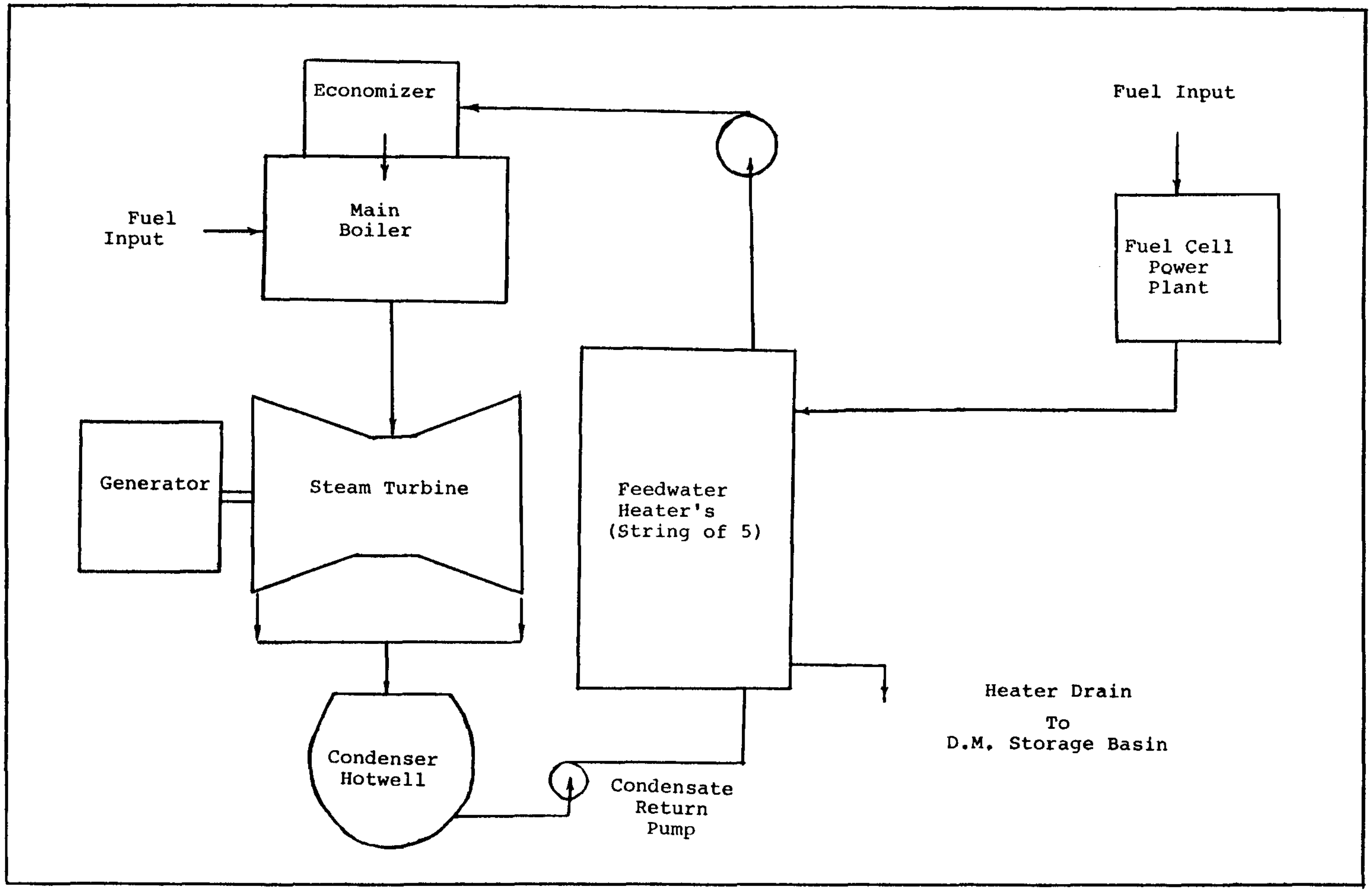

Figure 6-3. Block Diagram of Typical 1000 MW Unit Utilization of Fuel Cell Waste Heat.

Table 6-6

COST DATA FOR UTILITY APPLICATION OF DEUS FUEL CELL
(1975 dollars)

Data Item	Fuel Cell Type 1	Base Load Coal-Fired Unit
Fixed O&M (\$/kW-yr)	.26	4.0
Variable O&M (Mills/kW-hr)	2.85	1.0
Fuel Cost (\$/10^6 Btu)	2.45	1.20
Size (MW)	4.5	1000
Heat Rate (Btu/kW hr)	9300	9500
Availability (%)	92.2	71.5
Forced Outage Rate (%)	4.0	17.0
Incremental Energy Cost		
On-Peak	30.4 mills/kW-hr	
Off-Peak	21.3 mills/kW-hr	
Capacity Credit*	\$22/kW-yr	

* A capacity credit is developed at the installed cost of a combustion turbine. (\$120/kW at a carrying charge of 18%)

Source: Economic Assessment of the Utilization of Fuel Cells in Electric Utility Systems, PSE&G 1976

Table 6-7

DEUS FUEL CELL ECONOMIC EVALUATION AIR PREHEAT APPLICATION

(Thousands of Dollars, Except as Noted)

ITEM	1000 MW Base-load, coal-fired plant with ten 4.5 MW Fuel Cells	400 MW Intermediate-load, coal-fired plant with four 4.5 MW Fuel Cells	400 MW Intermediate-load, oil-fired plant with four 4.5 MW Fuel Cells
<u>Credits to Fuel Cell</u>			
• Replacement capacity credit for substitution of bleed steam	2740	780	700
• Net credit due to electricity production	50	260	260
• Total credits	2790	1040	960
<u>Costs to Fuel Cell</u>			
• Capital charges for plant modifications	40	20	20
• O&M costs	50	30	30
• Total Costs	90	50	50
Net Annual Credit	2700	990	910
Δ BECC	317 $/kW	291 $/kW	268 $/kW

Table 6-8

DEUS FUEL CELL ECONOMIC EVALUATION FEEDWATER HEATER APPLICATION

(Thousands of Dollars, Except as Noted)

ITEM	REPLACEMENT OF BOTTOM HEATER		REPLACEMENT OF TOP AND BOTTOM HEATER	
	1000 MW Base Load Nuclear or Fossil Plant with 396 MW DEUS Fuel Cell	400 MW Intermediate Load Fossil Plant with 58.5 MW DEUS Fuel Cell	1000 MW Base Load Nuclear or Fossil Plant with 198 MW DEUS Fuel Cell	450 MW Intermediate Load Fossil Plant with 72 MW DEUS Fuel Cell
<u>Credits to Fuel Cells</u>				
o Replacement capacity credit for substitution of bleed steam	5320	200	4610	600
o Net credit due to Electricity production	410	920	210	1130
o Total credits	5730	1120	4820	1730
<u>Costs to Fuel Cell</u>				
o Capital charges for plant modifications	50	50	90	50
o O&M costs	50	20	30	30
o Total costs	100	70	120	80
Net Annual Credits	5630	1050	4700	1650
ΔBECC	75 $/kW	95 $/kW	126 $/kW	121 $/kW

Table 6-9

UTILITY APPLICATION FUEL SAVINGS

APPLICATION	1000MW Base Load Units		400MW Intermediate Units	
	Percent Savings	Annual Savings (10^9 Btu/yr)	Percent Savings	Annual Savings (10^9 Btu/yr)
Air Preheating				
Coal Burning Units	7	239	6.1	48.0
Oil Burning Units	-	-	6.3	46.8
Feedwater Heating				
Bottom Heater	7	1800	6.9	140
Top & Bottom Heater	7	943	6.8	176

Fuel savings for the applications discussed are shown in Table 6-9. A maximum of 300,000 barrels of oil equivalent per year are saved with bottom feedwater heating in base load units.

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Section 7

IMPLICATIONS OF DEUS FUEL CELLS FOR UTILITY SYSTEMS

As has been stated, fuel cells offer considerable potential benefits and have a significant impact on utility system development. This impact will vary for specific utility systems depending on environmental considerations, generation area fuel availability and cost, system load factor, location of load centers, and ratio of utility peak and intermediate loads to the base load. Fuel cell dual energy systems offer all the benefits of conventional fuel cells and several additional benefits as follows --

- Capital cost credits from the sale of thermal energy
- Increased efficiency of energy use
- Reduced thermal pollution
- Capacity credits due to energy end use substitution

This section summarizes the possible implications of DEUS fuel cells in electric utility systems. A comparison is made with the reject heat utilization characteristics of other prime movers. Finally, the potential benefits and limitations of DEUS fuel cells from the perspective of the electric utilities are identified.

COMPARISON WITH OTHER REJECT HEAT UTILIZATION CONCEPTS

Power Generation Options

The conversion of a strictly electricity-producing fuel cell to a dual energy use system adds a new dimension to the potential of the fuel cell. This study is based on the premise that the electricity-producing fuel is baseline for evaluation, and thus much of the analysis is incremental in nature, rather than absolute. Still, any evaluation of fuel cells operating in the DEUS mode must consider existing technology options for providing both electricity and thermal products.

Thermal and electric energy from a DEUS can be obtained by the processes of "topping" or "bottoming". Topping involves the utilization of thermal energy conventionally treated as reject heat from an electricity generation process, while in bottoming, the energy rejected from an industrial thermal process is used to generate electricity. Although fuel cells would most likely fall into the "topping" category, they are somewhat unique in that the thermal and electric outputs are very nearly equal. Other technical options for topping, and related options for bottoming are shown below.

TOPPING

- Extraction Turbines
- Backpressure Turbines
- Gas Turbines
- Gas Turbines/Waste Heat Boiler
- Diesel Engines
- Externally-fired Brayton cycles

BOTTOMING

- Low-pressure steam turbines
- Organic Rankine cycles
- Sterling cycles
- Brayton cycles

Most existing DEUS systems are either steam turbines, gas turbines or diesels. These power generation options are summarized below.

Steam Turbines. Steam turbines represent the most prevalent method for electric power generation. In a cogeneration or dual energy use system, steam is taken from the turbine at a pressure and temperature appropriate for the process energy needs (generally much higher than the energy conventionally rejected from a power plant). This is achieved by extracting the steam at an intermediate step in the turbine (extraction) or by having the steam exhausted from the turbine at a high pressure (back pressure). The result is a decrease in the amount of electricity produced per unit of steam and an increase in the availability of thermal energy.

Steam Rankine cycle systems are neither efficient nor economical except in very large sizes and are not satisfactory for smaller applications unless the demand for heat is so large that the electrical output can be considered a by-product. The ratio of heat load to electrical load should be on the order of 20 to 1 (1). This situation is brought about by the fact that small steam turbines are very inefficient when operated at high pressure and are incompatible with the conditions that give a high basic cycle efficiency. During the first step in the Rankine cycle, saturated liquid is pumped to a high pressure and energy is added by heating the fluid in a boiler at a constant pressure until it becomes saturated or superheated vapor. Useful work is extracted in the form of shaft power as this superheated vapor expands through the turbine. Reheating is used to increase the thermal efficiency of this cycle and the vapor is removed and reheated after expansion through later turbine stages.

Steam electric plants generate approximately 80% of electric energy in the United States at an electrical efficiency of between 30 and 40 percent. However, in the smaller ranges of up to 10 MW the electrical efficiency is in the range of 17 to 24 percent (1). Typical efficiencies of steam power plants are shown in Table 7-1.

Table 7-1

TYPICAL EFFICIENCIES OF STEAM POWER PLANTS

Plant Output (KW)	Electrical Efficiency (%)
7100,000	31-40
50,000 - 100,000	27-34
10,000- 50,000	22-31
1,000 - 10,000	17-24
<1,000	7-19

Source: G. Samuels, et.al., MIUS Technology Evaluation, Prime Movers, Oak Ridge National Laboratory, for U.S. Department of HUD, ORNL-HUD-MIUS-11, April, 1974

Gas Turbines. Gas turbines are also conventionally used for power generation, however, a primary use is to meet intermediate or peak demands. The exhaust from a gas turbine can be used as hot air for process use or passed through a waste heat boiler to generate steam. For a given quality of steam requirements, gas turbines can produce more electricity than steam turbines. However, under present technology, gas turbines need natural gas or light distillates as input fuels, while large steam turbine installations can use coal-fired boilers. Small gas turbines, because of their relatively low electrical efficiency and high excess air requirements, are of interest in applications in which the heat usage is four to five times that for electricity.

The open cycle gas turbine (open Brayton cycle) is made up of a compressor, a combustion chamber and the gas turbine itself. The Brayton cycle has a low thermal efficiency not only because of compressor work requirements, but also because of high energy losses to the exhaust gas and mechanical losses in converting internal energy of the high temperature gases into turbine work. Many variations on the open Brayton cycle have been proposed, including a regenerative cycle, intercooled cycle, reheat cycle, compound cycle, and a closed Brayton cycle (accomplished by replacing the combuster with a tube and shell heat exchanger).

Diesel Engines. Diesel engines have a higher electrical conversion efficiency than gas turbines, but also require petroleum based fuels. Historically, diesel engines have been less attractive for on site generation, primarily due to the requirement for on site fuel storage facilities which add appreciably to the capital cost of the installation. A typical diesel engine used for power generation has a thermal efficiency ranging from 35 to 40 percent and the exhaust gases and the water jackets contain considerable heat that can be recovered. The diesel engine ignites the fuel by spontaneous combustion chambers with an accompanying reduction in the combined exhaust emission.

The size of the diesel engine influences its efficiency dramatically.

The maximum rpm's tend to be lower as engine size increases with a corresponding increase in the efficiency. The diesel engine is much more efficient than either of the open Brayton gas turbine or the small steam turbine at full and partial load. Among the emerging technologies for cogeneration is the low speed diesel which can operate on residual fuel oil. The engine has the advantage of high efficiency and can use low grade fuel. This is clearly not an experimental technology and large slow speed diesels have a proven record of reliability with operation on residual and crude oil in marine applications. Acceptable efficiencies have been sustained down to 30% of load and this generation option offers approximately twice the electricity per unit of steam as the gas turbine and ten times that of the steam turbine.

Gas Engines. Gas engines are well developed and commercially available for many applications, but do not account for any significant portion of electrical power production today. While the diesel engine operates on a compression ignition system, the gas engine, also reciprocating internal combustion, operates on spark ignition (Otto cycle) using natural gas or gasoline. The gas engine was introduced in many "total energy" systems during the early 1960's when natural gas was cheap and plentiful. In addition to natural gas, these engines can burn propane, butane or methane. The heat rate of a gas engine at reduced loads resembles a gas turbine (rather than a diesel) in that it increases rapidly at part load.

Fuel Cell DEUS Comparison

Fuel cells, using the electrochemical conversion process to generate electricity, can be used for cogeneration because they reject heat as part of the process. This reject heat, however, it limited to maximum of 120 psi and 350°F in the Type I fuel cell. Fuel cells compare rather favorably with the predominant prime movers identified earlier on the basis of relative energy efficiency, economics, and environmental and siting issues. there is no question that energy conservation will be accomplished in this country with improved energy conversion efficiencies, the development of dual energy use, combined cycles and cogeneration applications and fuel seitching from natural gas and light distillates to residual oils and coal derived heavy oils.

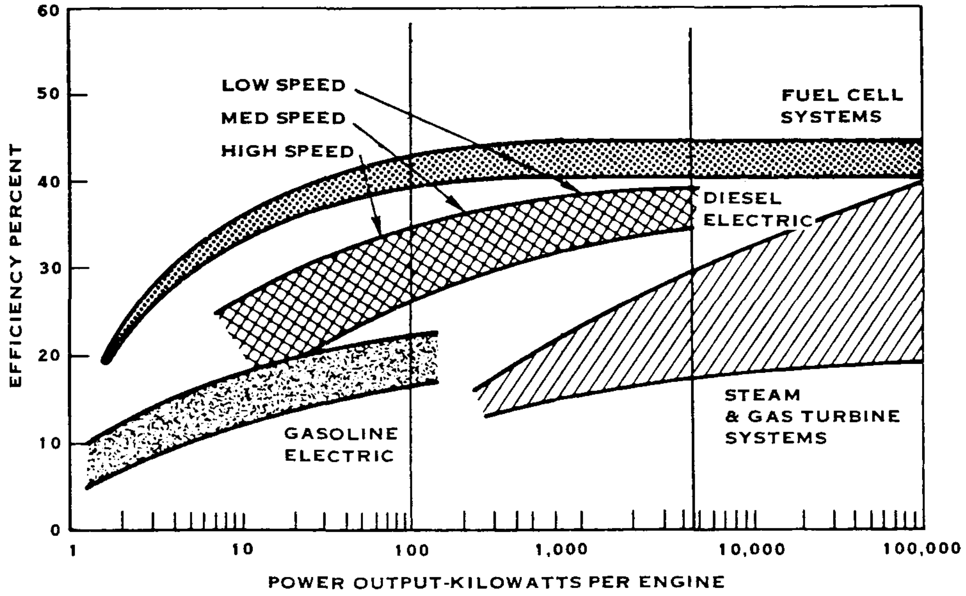

Figure 7-1. Power Generation Options Efficiency vs. Output

Source: Interstate Land Development, Inc., Preliminary Design Technical Report, MIUS Demonstration, St. Charles, Maryland, for U.S. Department of HUD, February, 1978.

A comparative overview of efficiencies for various power generation options is shown in Figure 7-1. Fuel cells and diesel engines appear to be the most favorable options from the electrical point of view with gas engines and steam and gas turbines significantly less attractive. However, when the power plant reject heat utilization capability of each of the prime movers is considered a different picture emerges. Examining a gas engine with heat recovery boiler, diesel engine with heat recovery, and extraction or back pressure steam turbines, the combined thermal and electric efficiency is a good measure of the DEUS applicability. Referring to Table 7-2, the typical heat balances of the five prime candidates for small dispersed power generators can be compared. It is interesting to note that the fuel cell has the second highest thermal and electric combined efficiency (80.9%) behind the gas engine (81.1%) but has numerous other advantages which make it appear more attractive for this application. From the electrical efficiency point of view, as we have seen, the fuel cell at

Table 7-2

TYPICAL HEAT BALANCES PER kWh OF ELECTRIC ENERGY PRODUCED

	INPUT (Btu's)	ELECTRIC (Btu's)	THERMAL (Btu's)	LOSSES (Btu's)	T/E Efficiency
Fuel Cell	9,000	3413	4120	1467	83.7%
Gas Engine	11,600	3413	6000	2187	81.1%
Diesel Engine*	8,751	3413	3124	2214	74.7%
Gas Turbine	20,000	3413	11,000	5600	72.0%
Steam Turbine*	12,200	3413	2800	5987	50.9%

(All Figures at PerCent Loading Which Maximizes Electrical Efficiency)

* 2-50 MW_e

Source : MATHTECH Estimates

approximately 40% is unquestionably more attractive than the gas engine at approximately 29%. Although the respective electrical efficiencies differ greatly between the diesel engine and gas turbine, the combined thermal/electric efficiencies are comparable (74.7% vs. 72.0%). The heat balances in Table 7-2 were computed on a respective engine loading which maximizes the electrical efficiency. In some cases this was as low as 60 or 70 percent, and average values were used whenever possible.

A second criterion under energy efficiency for comparison of reject heat utilization concepts is the quality of the heat recovered. Table 7-3 is the exhaust temperature for the five power generators considered. It can be seen that only the gas turbine and steam turbine provide high enough temperatures for a process application. The advanced technology fuel cells may also provide a small amount of reject heat of temperatures approaching 1000°F. On the other hand as Table 7-2 shows, the gas turbine and steam turbine rank at the bottom for combined thermal and electric efficiency. For space heating and cooling, domestic hot water, and process applications,

Table 7-3

QUALITY OF RECOVERED HEAT

Type of Generation	Electrical Efficiency	Temperature of Reject Heat
Gas Turbine	17-30%	800°-1000°F
Steam Turbine	17-31%*	650°-1000°F
Diesel Engine	38-40%*	700-800°F
Fuel Cells (Type I Phosphoric Acid)	38%	160-350°F
Fuel Cells (Type II Molten Carbonate)	48%	140-1030°F
Gas Engines	29-32%	1000-1200°F

* 2 to 50 MW(e) range; turbine efficiency also determined by throttle pressure and operating temperature

the value of the fuel cell is apparent. The good electrical efficiency, thermal recovery and acceptable quality of the recovered heat make this option appear viable.

Economics. The variable to be considered when evaluating the economics of power generating options is the installed capital cost. Referring to Table 7-4, the capital cost (based on 1975 dollars) expressed in dollars per kilowatt is given for each option. Fuel cells are near the top of the spread. Gas turbines appear very attractive and should continue to be a viable selection for peaking and various modes of standby service. Both the economics of the steam turbine and its combined thermal/electric efficiency of 51% makes this a relatively unattractive option for a dual energy use system.

Environmental and Siting. Items of obvious concern in this area include emissions, noise, proximity to thermal consumer, and siting area required. The minimal environmental effect and tremendous siting flexibility are perhaps the major strengths of fuel cells when compared to the other options discussed. Very low emissions, an absence of significant noise, water conserving nature, and their

Table 7-4

POWER GENERATION OPTIONS WITH HEAT RECOVERY

	INSTALLED CAPITAL COSTS ($/kw) (1975 Dollars)
Gas Turbines	165
Fuel Cell (Type I - Phosphoric Acid)	290
Diesel Engine	340
Gas Engine	345
Steam Turbine	415

NOTE: Figures include following numbers for adding heat recovery: Gas Turbine - $20/kW; Steam Turbine - $15/kW; Gas Engine - $25/kW Diesel Engine - $35/kW; Fuel Cell - $15/kW.

SOURCE: EPRI Technology Assessment Guide, August, 1977; G. Samuels, et. al., MIUS Technology Evaluation, Prime Movers, Oak Ridge National Laboratory, for U.S. Department of HUD, ORNL-HUD-MIUS-11, April, 1974.

resulting attractiveness for on-site application are all positive factors for the fuel cell.

Overview of Comparison

The advantages and disadvantages of the various power generating options are shown in Table 7-5. Advantages given for the fuel cell are summarized as follows:

- siting flexibility -- combined with reduced construction lead time because of modular design
- high efficiency -- greater than that for conventional thermal generators
- flexibility on sizing -- fuel cells are of modular design, such that small fuel cells operate as efficiently as large ones
- potential multi-fuel capability (but all premium fuels)
- environmentally attractive -- low emissions, quiet operation, and limited water requirements
- flexibility on load variation -- good part load performance

Table 7-5

CHARACTERISTICS OF TECHNICAL OPTIONS

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
Steam Turbines	o Long Life o Can Burn Coal and Other Non-Premium Fuels o Technology Well Established and Understood	o Low Electric Efficiency o Uneconomic at Small Sizes o Plant Cannot Be Operated Unattended (High Labor Burden) o Requires Large Siting Area
Gas Turbines	o High Temperature Heat o Better Efficiency o Compact, Lightweight, Easily Set Up o Reduced Maintenance Requirements o Short Lead Time o Good Reliability	o Petroleum Based Fuels o Thermal/Electric Efficiency Low o Noisy (siting restraints)
Diesel and Gas Engines	o Reliability o High Efficiency o Small/Intermediate Size o Lower Fuel Use than Gas Turbine for Spinning Reserve (50%)	o Siting of Storage Tanks o Low Waste Heat o Petroleum Based Fuels
Fuel Cells	o Siting Flexibility o Flexibility on Sizing o Potential Multifuel Capability o Environmentally Attractive o Flexibility on Load Variation o High Efficiency	o Low Temperature Heat o New Technology o Petroleum Based Fuels

As has been stated, the exact role of fuel cells in the future generating mix of the utility would depend on a number of factors including the system load duration curve, capital and operating cost of alternative technologies, and the existing generation mix.

POTENTIAL BENEFITS

All the benefits associated with a fuel cell dual energy use system are derived from the two primary unique features of the fuel cell -- its inherent design modularity and the fact that it is based on electrochemical process. The fuel cell characteristics and specific benefits that result from these features are shown in Figure 7-2 and are discussed below. The electrochemical process of the fuel cell leads to certain characteristics which enhance the attractiveness of the fuel cell for certain applications. The relatively flat heat rate of the fuel cell and resulting excellent part load efficiency combined with the heat rejection independence of the electricity production mode lead to substantial energy conservation and energy savings with this means of power production. Again, since the fuel cell is a chemical process and not an engine, the machine is not limited by the Carnot cycle efficiency. The resulting electric and thermal efficiencies associated with the fuel cell also contribute to the energy conservation potential.

Another major benefit associated with the electrochemical process is the environmental acceptability of the fuel cell due to the extremely low emissions, water conserving nature, and quiet operation. The static type generation method also leads to improved reliability and an inherent spinning reserve capability unique to this machine. No startup is required and along with the ease of maintenance and operation associated with a static process significant economic savings and ease of grid connection can be realized. Environmental acceptability is especially important to dual energy use systems because of the desirability of siting these systems next to thermal consumers.

The second feature of the fuel cell, modularity of design, leads to the following five primary characteristics that contribute to the potential benefits.

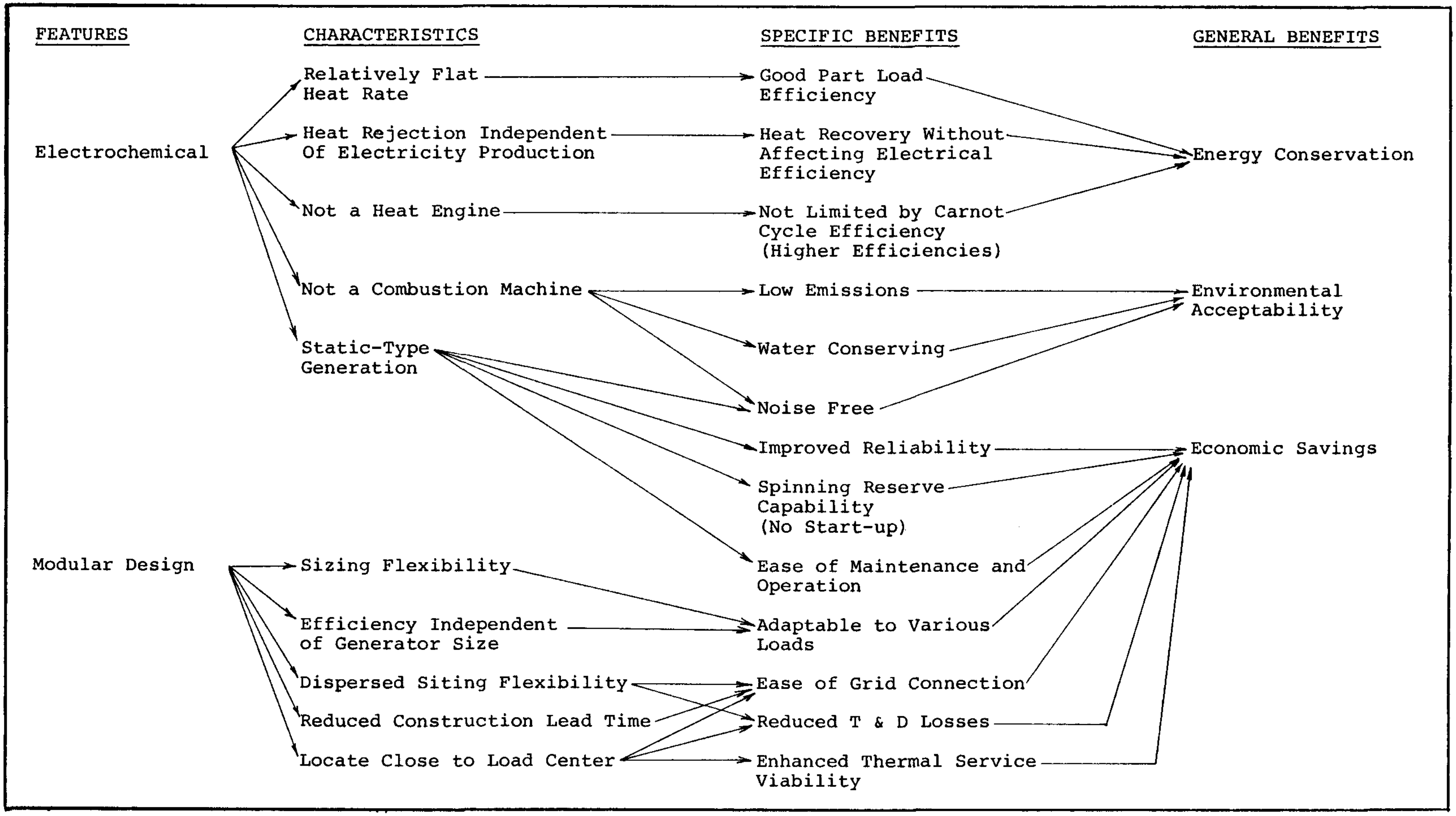

Figure 7-2. Potential Benefits of Fuel Cell DEUS.

- sizing flexibility
- efficiency independent of generator size
- dispersed siting flexibility
- reduced construction lead time
- abiltiy to locate close to load centers

The last item, associated with reduced transmission and distribution losses and enhanced thermal service reliability, are major components of the potential economic savings. Modularity is especially important to DEUS's because of the importance of matching thermal capacity to specific thermal demands.

Other benefits of a fuel cell DEUS are the siting flexibility for thermal production and heat recovery without affecting electrical efficiency. Additionally, DEUS operation of fuel cells results in capital cost credits to the utility from the sale of thermal energy.

POTENTIAL LIMITATIONS

The limitations on utility uses of fuel cells include quality of heat, problems of matching thermal and electric loads, heat recovery and distribution costs, and some operation issues. Because of the dual energy provided by DEUS fuel-cell installations, the application limitations are considered from both the electric and thermal system viewpoints.

Quality of Heat

In general, the quality of heat provided by the Type I fuel cell is satisfactory for most residential and commercial applications. For some industrial and utility power-plant applications the temperature and/or pressure of the fuel cell waste heat is not sufficient to meet all major requirements. For the utility power plant applications, for example, the Type I fuel cell provides an acceptable quality of heat for the air preheater, the HVAC and other minor auxiliary steam requirements. However, in the case of the feedwater heating application, the Type I fuel cell does not provide sufficient quality heat to make this application economically desirable.

When more data is available for the Type II fuel cell it is anticipated that the availability of higher quality heat may make the feedwater heater application, as well as certain industrial applications, more attractive.

Matching Thermal and Electric Loads

One operating strategy examined during this study was thermal load following. Under this operating strategy, certain applications, such as a hospital, require an almost constant supply of heat necessitating near continuous operation of the fuel cell. Depending on the utility's electric generation mix, base load units may be forced to operate at reduced output to accommodate the thermal requirements of the DEUS installation.

Operation

The operating requirements of various DEUS fuel-cell installations depend on the related support facilities to be provided with DEUS, i.e., whether back-up thermal supply and/or thermal storage is provided with each DEUS installation. A DEUS must be operated to meet overall thermal supply needs of each load, and these considerations have been discussed in previous sections. The economic impact of such fuel cell operation on the electric system should be recognized in the planning and operating evaluations.

From the electric supply standpoint, the maximum amount of fuel-cell generation installations that can economically be absorbed by the utility is a limiting function. This maximum amount is a function of

- the optimum amount of peaking or intermediate generation to be provided
- existing amount of such generating capacity to be retained for the foreseeable future

Previous studies by electric utilities have concluded that the optimum amount of peaking or intermediate generation should be in the order of 20 to 30 percent of total installed generating capacity. Considering the availability of existing capacity relegated to peaking or intermediate-duty operation, it appears that a maximum amount of 10% of total generating capacity should be considered for fuel-cell installations in the near future. Over the long term, this fraction may increase to from 20 to 30 percent, provided that fuel cells are economically competitive with other advanced concepts of peaking or intermediate generation. Therefore, the maximum amount of DEUS fuel cell installations that could be absorbed by an electric utility must be measured by these optimum capacity ceilings defined from the electric system standpoint.

The operating requirements of DEUS fuel cells from the thermal supply standpoint have been discussed above. If these fuel cells can be operated on the basis of electric system economic dispatch while satisfying the thermal supply constraints, then there would be no economic penalty from the electric system standpoint. However, if substantial deviations from electric system economic dispatch is required to satisfy the thermal supply needs, the associated DEUS fuel cell production cost penalties from the electric system standpoint must be recognized and taken into account in both planning and operating evaluation. The extent of this potential limitation was examined in the economic evaluation of overall DEUS operation in Sections 4-6 of this report.

REFERENCES

1. G. Samuels, et. al., MIUS Technology Evaluation, Prime Movers, Oak Ridge National Laboratory, for U.S. Department of HUD, ORNL-HUD-MIUS-11, April, 1974.

Section 8

CONCLUSIONS

VIABILITY OF DEUS FUEL CELL APPLICATIONS

The results of the evaluation of the applications in the residential/commercial, industrial and utility sectors, described in Sections 4-6, indicate that DEUS fuel cells are technically feasible and economically attractive. A summary of the results for the generic applications examined in this study is given below.

Building System Applications

Out of the eight building system applications selected for evaluation, seven were found to be economically viable. The other, an urban central business district, is economically viable when the utility-owned fuel cell DEUS is not charged with the installation and operation of the associated thermal distribution system. The most promising applications analyzed were the hospital and university, which resulted in capital cost credits that ranged from 211 \$/kW to 451 \$/kW. Capital cost credits typically increased by 50 to 100 percent when the price of #2 fuel oil was increased from \$2.45/10^6 Btu to \$3.50/10^6Btu, due to the higher value of the utilized reject heat.

One important finding was that the economic viability of these applications does not depend on thermal dispatch operation of the fuel cell DEUS. Instead, the DEUS may be operated according to the economic dispatch options of the utility at only a modest economic penalty relative to thermal dispatch operation.

Fuel cell dual energy use systems resulted in energy savings of from 18 to 38 percent over conventional fuel cells and separate heat production systems. Although, somewhat greater energy savings resulted for thermal dispatch, as opposed to economic dispatch operation, deviations from economic dispatch may result in either

- the displacement of base load generation that consumes abundant, rather than scarce, energy resources, or
- the increased operation of high cost, and sometimes less efficient peaking units.

Thus, the energy supply impact of thermal dispatch operation must be assessed carefully for specific DEUS applications and host utilities.

Industrial Applications

All of the eleven industries analyzed are promising applications for a fuel cell DEUS. The most promising application is Pulp and Paper Mills (SIC's 2611, 21, 31, 61), which resulted in capital cost credits of from 367 \$/kW to 403 \$/kW. Both economic and thermal dispatch operation were economically attractive for industrial applications.

DEUS fuel cell operation resulted in boiler fuel savings as high as 100 percent. However, utility fuel shifts can occur, and base load fuel resources, such as coal, nuclear, and hydro may be saved at the expense of the premium fuels when DEUS fuel cells are operated in the thermal dispatch mode.

The Type II - molten carbonate fuel cell is more appropriate in plants with significant process heat requirements in the 350 to 500°F range (in addition to low temperature requirements). However, they are slightly less attractive than Type I - phosphoric acid fuel cells for dual energy use, because of their lower rate of heat rejection.

Utility Applications

Several applications of DEUS fuel cells to large steam power plants were analyzed. The use of fuel cell reject heat rather than bleed steam for air preheating and boiler feedwater heating resulted in capital cost credits of from 75 \$/kW to 317 \$/kW. The air preheating application is attractive for both intermediate and base load plants. However, the feedwater heating application is recommended only for intermediate load plants, because of the large amount of fuel cell capacity that would be required to support a base load plant. The applications of DEUS fuel cells for power plant HVAC and auxiliary steam requirements is feasible when coupled with either of the above requirements.

IMPLICATIONS FOR NATIONAL ENERGY POLICY

The widespread utilization of DEUS fuel cell systems could have significant national implications in the following areas:

- energy savings
- fuel mix
- environmental impacts
- capital requirements
- transmission and distribution losses

Each of these is briefly discussed below.

Energy Savings

Each of the applications examined in this study indicated an energy savings for a fuel cell DEUS vs a conventional (non-DEUS) fuel cell and boiler. DEUS fuel consumptions were typically 10 to 30% lower than those for conventional systems. If DEUS fuel cells were implemented for all possible applications examined in the study, the total annual energy savings could be 1500 trillion Btu (250 million barrels of oil equivalent). From this perspective it is clear that DEUS fuel cells are consistent with national energy policy. It should be pointed out, however, that the dispatch of DEUS fuel cells to meet thermal rather than electric needs could imply some displacement of coal and nuclear by petroleum. Since this is undesirable, economic (electric) dispatch is to be favored with a lower energy savings than described above. This is discussed further below.

Fuel Mix

DEUS fuel cells will need petroleum based fuels. To the extent that these fuel cells replace intermediate power generation resources fired by petroleum based fuels and petroleum based thermal generation at the application site, DEUS fuel cells will offer a significant potential for energy savings with little or no change in fuel mix. However, if these fuel cells replace coal-fired industrial boilers or coal or nuclear base-load generation, they would cause significant shifts in fuel use patterns, and substitution of scarce imported fuels for more abundant resources. Such situations may be avoided by careful selection of the DEUS application. In some cases there may be a trade-off between the desirable effects of conservation and a cleaner environment and the undesirable effect of the substitution of oil for coal. An exact measure of these effects cannot be made without a specific analysis of the current and projected generating mix of each utility and an analysis of the specific thermal applications.

Environmental Impacts

In general, fuel cells are environmentally desirable because of low emissions, low water needs, quiet operation and aesthetics. However, the location of DEUS fuel cells near load centers would result in a shift of the emissions from central stations to these dispersed locations. Also, to the extent that DEUS fuel cells result in fuel mix changes, the types of emissions or other environmental impacts will vary. In general, however, fuel cells tend to be more acceptable from an environmental standpoint than any type of generation they are likely to replace.

Capital Requirements

The capital requirements for fuel cell power plants per kW are expected to be less than those for larger central station plants. To the extent that capital requirements pose a constraint to growth in generating capacity, fuel cells provide a viable option. Also, assuming that fuel cells are economically viable for power generation, their use in the DEUS mode may result in capital savings at the application site. On the other hand, utility ownership and operation of DEUS fuel cells will imply somewhat increased capital needs for utilities (who are more capital constrained) and less for industries or building system owners.

Transmission and Distribution Losses

Dispersed fuel cells located at or near load centers will require less transmission and distribution facilities over the long term than conventional power systems and would also result in smaller transmission and distribution losses.

POTENTIAL FUEL CELL MARKET

The potential market for fuel cells in large and small utilities was estimated by PSE&G (1) and Burns and McDonnell (2). If fuel cells achieve the market penetration determined by those studies, it is likely that a large number of these will operate in the DEUS mode. An accurate estimate of the market potential is beyond the scope of this study, as it would require an analysis of specific utilities and the existence of the residential/commercial and industrial applications within these utilities.

However, based on the information generated in this study of the generic applications, a rough estimate of the maximum market potential for these applications can be made. If all the applications which were economically very viable were considered, the total market potential would be as follows:

Applications	Approximate Number of Applications in United States *	Typical DEUS Fuel Cell Size Based on Thermal Requirements (MW)
Building Systems:		
Hospital	1400	11
Residential Development	no estimate made	4.5
Shopping Center	1700	1
Office Building	several thousand	3
University	100	4.5
Military Base	300	4.5
Residential/Commercial	no estimate made	4.5
Central Business District	100-200	117
Industrial Systems:		
Cane Sugar Refining	18	18
Beet Sugar Refining	54	14
Distilled Liquors	37	9
Finishing Plants, Cotton	50	18
Finishing Plants, Synthetic	99	27
Paper & Pulp Mills	446	18
Non-cellulosic Fibers	46	90
Cyclic Crudes & Intermediates	60	104
Petroleum Refining	182	14
Utility Systems:		
1000 MW Base-Load Plant	97	45

* The sources of these estimates are as follows: Building Systems-Mathtech estimates; Industrial Systems-General Energy Associates estimates; Utility Systems-Federal Power Commission (3).

RESEARCH AND DEVELOPMENT NEEDS

This study has identified a number of areas where further research is needed.

- thermal energy utilization profiles- information on temporal profiles of thermal energy use, particularly in the industrial sector, is very weak. Also information on central business district and profile needs to be improved.

- value of thermal energy - in this effort, the value of thermal energy was assumed to be equal to the cost of producing energy with a conventional system. More accurate calculation of this value and the determination of what potential DEUS customers would actually be willing to pay for thermal energy are needed. Since the economics of the DEUS fuel cell are extremely sensitive to the value of thermal energy, this area would be an important research item.

- heat recovery configurations - A fuel cell manufacturer will be economically limited in his ability to produce a large number of catalog configurations to meet the specific needs of the many applications indicated by this study. Therefore, the more promising applications should be screened, and two or three DEUS plant configurations should be selected that best match a significant number of these applications.

- customized fuel cell designs - for certain applications, it may be desirable to develop customized fuel cell configurations. The cost and mass production implications of such designs need to be investigated.

- modifications to Type II fuel cell - since the Type II fuel cell can produce higher quality thermal energy, possible modifications which could increase the quantity and quality of thermal energy should be investigated.

- integration with high temperature heat pumps - the technical and economic feasibility of a DEUS fuel cell with a high temperature heat pump should be investigated. Such a combination would provide flexibility to satisfy a large number of different types of loads. The capital costs and performance characteristics of high temperature heat pumps need to be assessed.

REFERENCES

1. Public Service Electric and Gas Company, Economic Assessment of the Utilization of Fuel Cells in Electric Utility Systems, EPRI EM-336, Final Report, November 1976.

2. Burns and McDonnell Engineering Company, An Assessment of the Fuel Cell's Role in Small Utilities, EPRI AF-696, Final Report, Volume 1, February 1978.

3. Federal Power Commission: Steam-Electric Plant Construction Cost and Annual Production Expenses, Washington, D.C., 1974.

Appendix A

GLOSSARY

a.c. - alternating current

baseline option - a specific DEUS plant design/operating strategy combination selected as representative for the discussion and comparison of results.

baseline results - results of DEUS economic and energy supply evaluations for baseline options (described above).

baseload plant (or unit) - an electrical generating plant or unit that is most economically used in supplying a utility's base-load demand. Such plants (or units) typically operate at least 70 percent of the time (1).

C_{aux} - capital cost of all DEUS plant auxiliary systems (e.g. boilers, thermal storage, etc.), normalized by fuel cell electrical capacity ($/kW).

CBD - central business district (of a city)

CC - carrying charge rate, including return, depreciation and taxes, for utility capital items. (A carrying charge rate of 0.18 was assumed in this study for all plants and equipment.)

CCIF - Construction Compound Interest Factor, a constant multiplier that "reflects the obligation for the actual cost of money incurred by a utility during the construction period which must be recovered during the useful life of the plant. Installed cost is multiplied by CCIF before calculating the carrying charges (2).

C_{HR} - capital cost of all heat recovery modifications made to a particular fuel cell DEUS.

Configuration A - one of several fuel cell heat recovery modifications considered for DEUS operation. Configuration A includes minimum modifications to the fuel cell and provides all thermal energy in the form of 210°F hot water.

Configuration B - one of several fuel cell heat recovery modifications considered for DEUS operation. Configuration B includes those fuel cell modifications necessary to provide some thermal energy in the form of 120 psig steam at a temperature of 350°F. The total heat recovered, however, is the same as for Configuration A.

Configuration C (Options I and II) - one of several fuel cell heat recovery modification considered for DEUS operation. Configuration C includes two options under which the fuel cell is modified to generate additonal thermal energy over and above that rejected in the electric power generation process. Both Options I and II result in additional 120 psig steam at 350°F. Option I requires no modifications to coolant loop hardware, but results in decreased amounts of additional steam as the fuel cell approaches rated electrical output. Option II does require coolant loop hardware modifications but results in a constant amount of additional heat over the entire electric power output range.

Cogeneration - according to the Massachusetts' Governor's Commission on Cogeneration (1), cogeneration is"the simultaneous production of electricity .... and useful heat in a way that requires less fuel than separate production of heat and electricity."

Conventional fuel cell - a fuel cell power plant that was designed for the production of electricity only and has not been specially modified so as to produce useful thermal energy.

COP - coefficient of performance as for a heat pump; a ratio of useful energy output to useful energy input for a given energy conversion device.

d.c. - direct current.

DCT - dry cooling tower, for the rejection of heat to the atmosphere; typically accomplished by passing cool air over a heat rejection surface.

Demonstrator (or 4.5 MW Demonstrator) - a first generation phosphoric acid, fuel cell power plant with a rated electric power output of 4.5 MW, designed by United Technologies Corporation and jointly funded by the U.S. Department of Energy and the Electric Power Research Institute.

DEUS - a system designed to supply both electricity and heat as mutual products of the same energy conversion process, as in cogeneration (defined previously).

DHW - domestic hot water.

DU - dwelling unit, residential.

E_{cap} - electrical capacity of fuel cell (kW).

economic dispatch - a DEUS plant operating strategy under which the plant's instantaneous electrical output is varied so as to minimize the reference utility's overall production costs and thermal energy is produced as a by-product.

EPRI - Electric Power Research Institute, Palo Alto, California.

feedwater - water that enters the intake, or "feed" of a boiler to be heated and released as steam.

G&T Cooperative - Generation and Transmission Cooperative, a group of utilities that have formed an association to allow for some degree of cooperation (or sharing) in the use of each other's power generating and transmitting facilities.

HVAC - heating, ventilating, and air-conditioning; a commonly used acronym for three building services that are often provided by a common system.

heat balance - a fractional breakdown of the thermal energy input (e.g. from the combustion of fuel) to a given process into the various energy outputs (specified by type and amount of energy) of that process.

HEX - heat exchanger, a device for transferring heat from one heat conducting medium (e.g. air or water) to another, or from one system to another.

hydro - short for hydroelectric, as in hydroelectric generating facility.

hydronic - of or having to do with "... electrically controlled systems for heating (and) cooling ... by the forced circulation of liquids or vapors. (3).

incremental breakeven capital cost - the amount by which the DEUS fuel cell's capital cost can change from that of a conventional fuel cell without affecting the life cycle cost of owning and operating a fuel cell power plant.

incremental energy cost - the cost to the reference utility at any given time and load level of producing an additional increment of electrical energy.

intermediate load demand - those levels of utility system electrical demand that are lower than peak load demands and higher than baseload demands, typically occurring greater than 33 percent of the time and less than 70 percent of the time.

intermediate load plant (or unit) - electrical generating plant (or unit) that is most economically used to supply intermediate load demands.

load matching/decoupling - the processes associated with balancing the electrical and thermal outputs of a dual energy use system so as to meet the simultaneous fluctuations in both these loads.

MFHR - multi-family, high rise, a type of residential development; assumed in this study to consist of 10-story buildings, with six dwelling units per story, 900 ft^2 per unit, and 30 units per net residential acre.

MFLR - multi-family, low rise, a type of residential development; assumed in this study to consist of 3-story, 24 unit garden apartment buildings, with 900 ft^2 per dwelling unit and 15 dwelling units per net residential acre.

O&M - operating and maintenance.

off-peak - defined for this study to be that 11-13 hour period of the day during which the reference utility experiences its lowest loads (typically 9p.m to 7a.m.).

on-peak - defined for this study to be that 11-13 hour period of the day during which the reference utility experiences its highest loads (typically 7 a.m. to 9 p.m.).

operating shift - the daily working hours (typically eight consecutive hours) for a particular segment of an industry's labor force.

operating strategy - a set of rules specifying the operating levels (electrical and thermal outputs) of a DEUS plant in response to any anticipated electric and thermal loads.

peak load demand - the highest levels of utility system electrical demand, typically those experienced only 33 percent of the time or less.

peak load plant (unit) - electrical generating plant (or unit) that is most economically used to supply peak load demands.

prototype building - one of several residential, commercial and institutional buildings (or groups of buildings) selected as a data source for analyzing building system applications of DEUS fuel cells.

PSE&G - Public Service Electric and Gas Company, Newark, New Jersey.

quality of heat - (for this study) a term referring to the temperature of available thermal energy; the higher the temperature, the higher the "quality."

reference utility - a hypothetical utility with characteristics that are representative of large U.S. electric utilities that would be likely to utilize fuel cells during the period 1980 to 2000; defined in a previous study for EPRI by PSE&G (2) and used here to represent the utility that would own and operate the various DEUS fuel cells that were analyzed.

reject heat - that thermal energy that ordinarily would be rejected from an electric power plant as a by-product of the electrical generating process.

SFA - single-family, attached, a type of residential development; assumed in this study to consist of two-story duplexes, each having two 1100 ft^2 dwelling units, with 10 units per net residential acre.

SFD - single-family, detached, a type of residential development; assumed in this study to consist of a number of one-story buildings, with one 1560 ft^2 dwelling unit per building and three units per net residential acre.

SIC - standard industrial classification, defined by the U.S. Department of Commerce.

supplemental boiler - a boiler that is added to a dual energy use system to provide either backup or a supplemental supply for use in satisfying thermal loads.

T_{cr} - annual credits resulting from the sale of thermal energy (dollars).

thermal dispatch - a DEUS operating strategy under which the DEUS thermal output is adjusted to meet the instantaneous demand for thermal energy and electrical energy is strictly a by-product.

thermal load following - used synonomously with the term "thermal dispatch."

TMS - thermal management subsystem, one part of the 4.5 MW (fuel cell) Demonstrator designed by United Technologies Corporation.

Type I fuel cell - a first generation fuel cell, generally requiring premium fuels (such as fuel oil and natural gas) and projected to be commercially available in the early 1980's.

Type II fuel cell - a second generation, or advanced technology, fuel cell, offering higher electrical efficiencies than Type I fuel cells and capable of utilizing low-sulfur distillate oil and clean-coal-derived liquids and gases; projected to be commercially available in the late 1980's.

UTC - United Technologies Corporation, South Windsor, Connecticut.

utility grid - the entire generation, transmission, and distribution network available to the reference utility.

ΔBECC - incremental breakeven capital cost.

ΔP - annual production cost increase due to DEUS operation of a particular fuel cell power plant (dollars).

ρ - annual total of all penalty costs incurred by DEUS plant deviations from economic dispatch operation (dollars).

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1. The Commonwealth of Massachusetts, Michael S. Dukakis, Governor, Cogeneration: Its Benefits to New England, Final Report of the Governor's Commission on Cogeneration, October 1978.
2. Public Service Electric and Gas Company, Economic Assessment of the Utilization of Fuel Cells in Electric Utility Systems, EPRI EM-336, Final Report, November 1976.
3. Webster's New World Dictionary of the American Language, College Edition, World Publishing Company, New York, 1957.

Appendix B

CALCULATION OF INCREMENTAL BREAKEVEN CAPITAL COSTS

The appendix describes the derivation of the DEUS plant "incremental breakeven capital cost", which was the primary economic performance index for this study. The key criterion in establishing such an index of DEUS fuel cell economic performance was that the index must consider only the economic differences between DEUS and conventional fuel cells. In previous studies (1,2) breakeven capital costs for utility-owned fuel cells had already been defined. Therefore, it was decided to evaluate the change in fuel cell breakeven capital cost when reject heat is utilized. This index, which is called the incremental breakeven capital cost (abbreviated ΔBECC), is the amount by which the DEUS fuel cell's capital cost can change from that of a conventional fuel cell without affecting the life cycle cost of owning and operating a fuel cell power plant. If this index is positive and greater than the capital cost of any fuel cell heat recovery modifications that might be required, the concept of a fuel cell DEUS would appear to be a good one.

Calculation of ΔBECC for any DEUS fuel cell requires only an understanding of what it means to "breakeven". Quite simply, the breakeven condition occurs when

$$\left\{\begin{array}{l}\text{Present worth of all}\\ \text{credits from the sale}\\ \text{of thermal energy}\end{array}\right\} = \left\{\begin{array}{l}\text{Present worth of all annual}\\ \text{cost increases of a DEUS}\\ \text{plant over a conventional}\\ \text{cell plant}\end{array}\right\} \qquad \text{(B-1)}$$

If annual costs and thermal energy sales are assumed constant and all capital costs are expressed in terms of a levelized fixed charge, Equation A-1 can be simplified to

$$T_{cr} = \Delta C \qquad \text{(B-2)}$$

where

T_{cr} = annual credits resulting from the sale of thermal energy

ΔC = annual cost increase associated with a DEUS versus conventional fuel cell power plant

The total cost may of course be broken into its components. Thus,

$$\Delta C = \Delta D + \Delta P + \rho \qquad \text{(B-3)}$$

where

ΔD = levelized annual fixed charge for all capital cost increases of the DEUS plant over a conventional fuel cell plant

ΔP = annual production cost increase due to DEUS operation

ρ = annual total of all penalty costs incurred by DEUS plant deviations from economic dispatch operation.

Finally, ΔD may be expressed in terms of actual capital cost increase of the DEUS plant as

$$\Delta D = (E_{cap} \cdot CC \cdot CCIF) \cdot \Delta C_{DEUS} \qquad \text{(B-4)}$$

where

E_{cap} = capacity of fuel cell (kW)

CC = carrying charge rate (assumed to be 0.18 for this study)

$CCIF$ = construction compound interest factor (1.05 for a fuel cell)

ΔC_{DEUS} = capital cost increase of the DEUS plant over a conventional fuel cell plant ($/kW)

When Equations A-2 through A-4 are then combined, ΔC^*_{DEUS}, the incremental breakeven capital cost of the DEUS plant is simply

$$\Delta C^*_{DEUS} = \frac{T_{cr} - \Delta P - \rho}{E_{cap} \cdot CC \cdot CCIF} \qquad \text{(B-5)}$$

If the DEUS plant includes any auxiliary equipment, such as boilers or thermal storage, their capital costs must be subtracted to arrive at ΔBECC for the DEUS fuel cell alone. Thus,

$$\Delta BECC = \Delta C^*_{DEUS} - C_{aux} \qquad \text{(B-6)}$$

where C_{aux} is the capital cost of all DEUS plant auxiliary systems normalized by the fuel cell electrical capacity ($/kW).

If this calculation is carried one step further and the cost of heat recovery is deducted from ΔBECC, it is possible to calculate a "net credit" to the fuel cell for reject heat utilization.
That is

$$\text{Net Credit for Heat Utilization} = \Delta BECC - C_{HR} \qquad \text{(B-7)}$$

Where C_{HR} is capital cost of all heat recovery modifications made to the DEUS fuel cell ($/kW).

Most of the terms in Equations A-5 and A-6 are easily understood. However, the penalty cost term ρ requires some additional explanation. As stated above, penalty costs were calculated for each hour of each day that the DEUS plant electrical production deviated from the prescribed economic (electric) dispatch levels. For a given day "j" and hour "k" the amount of this deviation was defined as $\Delta L(j,k)$. The annual penalty cost ρ was simply defined as the sum, over all hours and all days, of the differences in

- the cost of producing the quantity of electricity $\Delta L(j,k)$ by the DEUS plant, and
- the reference utility's cost of producing the same amount of electricity

In mathematical terms,

$$\rho = \sum_{j=1}^{N_d} \sum_{k=1}^{24} \{P_D(\Delta L(j,k),\ E_d(j,k)) - p_U(j,k) \cdot \Delta L(j,k)\} \qquad \text{(B-8)}$$

where

ρ = annual penalty cost (or credit, if negative) incurred by DEUS plant for deviations from economic dispatch operation (dollars)

j = index of representative day of year

k = index of hour of day

N_d = number of representative days

$P_D(\Delta X,Y)$ = hourly cost (dollars) of operating the DEUS plant at a level ΔX(kW) above the economic dispatch level of Y(kW), when ΔX is positive; when ΔX is negative, $P_D(\Delta X,Y)$ is also negative and is equal to the amount saved (dollars) by operating at a level ΔX(kW) below the economic dispatch level of Y(kW).

$\Delta L(j,k)$ = the amount (kW) by which the DEUS electrical production exceeds (or "is less than," if negative) the economic dispatch level during hour "k" on day "j"

$E_d(j,k)$ = economic dispatch level during hour "k" of day "j" (kW)

$p_U(j,k)$ = the reference utility's incremental energy cost during hour "k" of day "j".

As a simplifying assumption, the reference utility's incremental energy cost was assigned a single value for all on-peak hours and a different value for all off-peak hours. These values, which represent the annual average on-peak and off-peak incremental energy costs, respectively, for the reference utility, were

Time of Day	Incremental Energy Cost
• on-peak	.0304 $/kWh
• off-peak	.0213 $/kWh

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1. Public Service Electric and Gas Company, Economic Assessment of the Utilization of Fuel Cells in Electric Utility Systems, EPRI EM-336, Final Report, November 1976.

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