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W. David Lee, Siegfried Mathias
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Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
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1. EXECUTIVE SUMMARY

1.1 Background and Purpose

On-site fuel cell power systems offer substantial energy savings benefit to the public and uncertain benefits to the building developer or owner. On-site electric power generation reduces transmission and distribution losses and in the case of the fuel cell, provides auxiliary useful thermal energy for heating, cooling and ventilation building functions. The benefits that the fuel cell owner (building developer, utility, private leasing company) would realize stem from the net revenues generated by the fuel cell. These revenues are dependent on the capital costs and system performance of the total integrated on-site fuel cell system. This study focuses on the net benefits of an integrated fuel cell on-site power system as affected by the balance-of-plant equipment. Heating, cooling and ventilating equipment used in conjunction with the fuel cell to meet the necessary building demands can change the net revenues of the systems substantially. Over 100 system configurations were studied, annual operating performance, energy costs, capital costs and operating and maintenance costs were predicted using a computer program developed expressly for this project. Technical and policy alternatives were recommended that could improve the economics and competitive posture of on-site fuel cell power systems.

The work in this project was conducted by Arthur D. Little, Inc. with engineering support from R. G. Vanderweil Engineers and financial counsel from Urban Investment and Development Company.

1.2 Building and Fuel Cells Selected for this Study

Two buildings were selected by NASA-Lewis for this study as well as three types of fuel cells. Characteristics of the building and fuel cells were provided by NASA-Lewis to Arthur D. Little. A 112,000 sq.ft. garden apartment consisting of four buildings, each with twenty-four identical units was used as well as a retail store with about a 80,000 square foot floor area. The three fuel cells used in this study were applied to each of the buildings and balance-of-plant components were selected to match the particular qualities of the fuel cell. The fuel cells are characterized as follows:

- Fuel Cell A - air cooled, near term technology
- Fuel Cell B - liquid cooled, present technology
- Fuel Cell C - liquid cooled, advanced technology

Heating, cooling ventilation equipment designed by R. G. Vanderweil to meet the load requirement for the buildings were used in this study. System diagrams like the one in Figure S-1 were developed for analysis by a computer model that was used throughout the study. The model simulates the component interactions of the HVAC equipment under operations to meet the desired building load. While standard HVAC components were used in the model of the conventional (without fuel cell) system, additional HVAC components were needed for the future design work with fuel cells. R. G. Vanderweil developed a broad component data base of heating, ventilation and air conditioning equipment that could be used in conjunction with fuel cells. Included in this data base are the following major elements:

- electric chillers (centrifugal and reciprocating)
- absorption chillers
- gas boilers
- oil boilers
- electric boilers
- heat exchangers (steam/water, water/water)
- pumps
- thermal storage tanks
- cabinet heaters
- air handling units
- cooling towers

The component data base which can be found in Volume II, contains performance and cost data for all these components in a form to be compatible with the computer model of the system. In addition to component data, there are sub-systems consisting of common groupings of discrete compo-

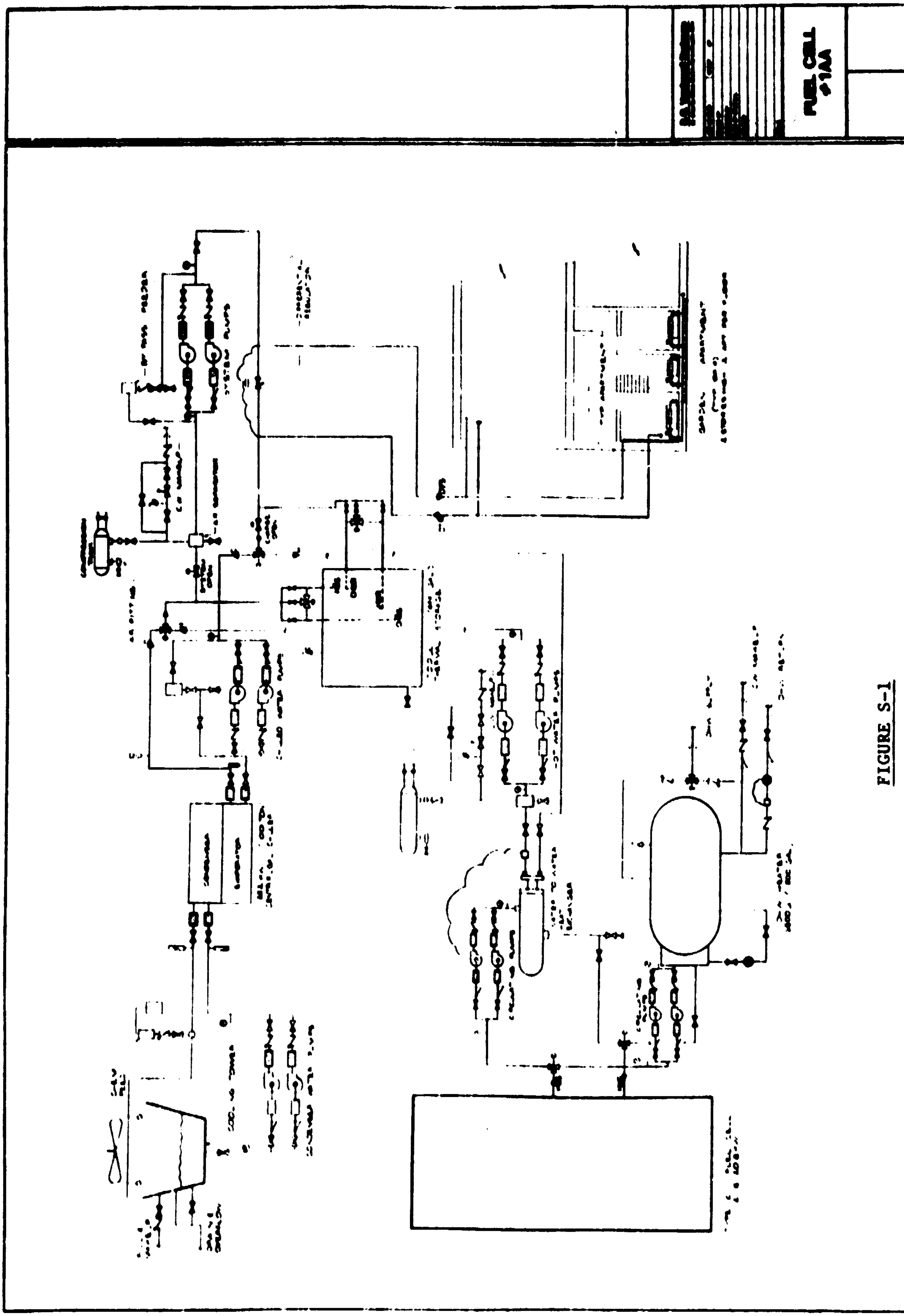

FIGURE S-1

nents. It was found necessary to develop these sub-systems so that interconnecting controls and pumps could be specified.

Contained in the computer model are cost data necessary for estimating the installed and operating costs of the HVAC system. As the user specifies components, the model sums the installed capital cost and with the predicted annual performance is able to provide complete system performance data as shown in Table S-1.

1.3 System Economics

Components were selected to work in combination to fully utilize the thermal energy from the fuel cell as it is required to meet the base electric demand. As numerous system trials were to be run it was clear that a figure of merit would be needed to guide the component selection process. NASA-Lewis recommended the levelized annual cost as the figure of merit and provided background material on the formulation of this quantity. The levelized annual cost is similar to a life cycle cost which includes the capital cost, interest rates of borrowed capital, depreciation and tax allowance, operating costs, and energy costs. Levelized annual costs were developed for over 100 system designs and are reported in Volume II, Section 3. The levelized annual cost (LAC) would only serve as a figure of merit for comparing similar systems to one another and that the economic feasibility of the project would have to be determined by the potential fuel cell owner (utility, building developer, leasing company) in a method consistent with the way they do business. Building developers would base their decision on a cash flow analysis and an internal rate of return calculation. These financial measures were developed for the first promising systems (lowest LAC) and are given in Tables S-2 and S-3 for the residential and retail buildings. All costs are in 1978 dollars.

The screening of system designs based on levelized annual cost is strongly influenced by the economic assumptions used in the LAC formulation. Key

TABLE S-1

CONVENTIONAL HVAC SYSTEM PERFORMANCE

(All Values Except Capital Cost are Annual Costs)

RETAIL STORE

	Levelized Annual $	Capital* $	Operating & Maintenance $	Total Energy $	Gas $	Electricity $
Gas	188952.12	258204.00	24465.12	119912.06	5312.49	114599.62
Electric	194535.87	243030.00	23620.90	129027.87	0.0	129027.87

GARDEN APARTMENT

	Levelized Annual $	Capital* $	Operating & Maintenance $	Total Energy $	Gas $	Electricity $
Electric	175498.50	174548.00	21493.44	122358.00	0.0	122358.0
Gas	143890.69	192548.00	22563.44	85188.87	20937.42	64251.47

* Piping Costs amounting to about $627,500 for the gas system in the store ($515,000 for electric) and $175,000 for the gas and electric apartment are not included.

TABLE S-2

RESIDENTIAL SUMMARY

SYSTEM NUMBER [1]	SYSTEM	AUXILIARY BOILER BACKUP	LEVELIZED ANNUAL COST IN $1,000 [2]	INTERNAL RATE OF RETURN [2]	CAPITAL COST IN $1,000 [2]
2A	Conventional Electric	-	175	Base	174
3A	Conventional Gas	-	144	-	192
1AA	21-21KW Fuel Cell A	-	149	34.0%	355
4AA	21-21KW Fuel Cell A	Boiler	150	32.0%	365
9BA	21-21KW Fuel Cell B	-	162	23.9%	424
10BA	21-21KW Fuel Cell B	Boiler	163	23.4%	431
5CA	5-129KW Fuel Cell C	-	154	26.3%	434
6CA	5-129KW Fuel Cell C	Boiler	155	25.6%	441

1 - Components comprising the system are given in Section 4.4 - Table 4A thru 4F.

2 - See Section 4.2 for an explanation of Levelized Annual Cost and Internal Rate of Return Compared to Conventional Electric. Section 3 of Volume 2 provides the complete financial analysis of each system, and Section 4 of Volume 2 gives the cash flow analysis of each system.

TABLE S-3

RETAIL STORE SUMMAPY

SYSTEM NUMBER[1]	SYSTEM	AUXILIARY BOILER BACKUP	LEVELIZED[2] ANNUAL COST IN $1,000	INTERNAL[2] RATE OF RETURN	CAPITAL COST[2] IN $1,000
2S	Conventional Electric	-	194.5	Baseline	243
1S	Conventional Gas	-	188.9	-	258
4AS	14-61KW Fuel Cell A	-	226.4	5.9%	584
5AS	14-45KW Fuel Cell A	Boiler	258.0	Negative	585
13BS	14-57KW Fuel Cell B	-	249.0	2.9%	732
17BS	14-44KW Fuel Cell B	Boiler	264.9	Negative	671
4CS	6-143KW Fuel Cell C	-	223.0	10.7%	692
5CS	5-144KW Fuel Cell C	Boiler	239.0	Negative	658

1 - Compone..ts comprising the systems are given in Section 4.4 - Tables 4A through 4F.

2 - See Section 4.2 for an explanation of Levelized Annual Cost and Internal Rate of Return compared to Conventional Electric. Section 3 of Volume 2 provides the complete financial analysis of each system, and Section 4 of Volume 2 gives the cash flow analysis of each system.

economic parameters used were:

- 20% before tax cost of capital
- .6% per year electric escalation cost
- 2.4% per year gas escalation cost
- Fuel cell costs of $350 to $500 per KW

The impact of the economic assumptions can be seen in Table S-4. A reduction in the cost of capital to 15% (closer to the prime lending rate) will dramatically effect the LAC; making two of the apartment systems (Fuel Cell A and C) competitive with a conventional gas system. A 25% reduction in fuel cell costs has about the same effect and can make apartment systems with Fuel Cell A and C attractive.

These results demonstrate the importance of developing consistent and credible fuel cell capital costs for feasibility analysis. In addition, attention should be given to qualifying the fuel cell system for conventional commercial loans at or near the prime lending rate (less than 15%), by convincing the financial community of the demonstrated reliability and fuel cost savings of the on-site fuel cell system. Projections of gas and electric escalation rates should be updated and incorporated in future studies.

1.4 Component Analysis

1.4.1 Sensitivity Analysis

The effect of component selection of the two key measures of performance:

- Energy Cost Savings
- Levelized Annual System Cost

was examined in a sensitivity analysis. Table S-5 summarizes the effect of component selection on energy cost savings and Table S-6 gives the effect on levelized annual cost.

TABLE S-4

ECONOMIC PARAMETERS SENSITIVITY ANALYSIS
PERCENTAGE SAVINGS IN LAC OVER CONVENTIONAL GAS

Building		Residential			Store		
Fuel Cell		A	B	C	A	B	C
System		1AA	9BA	5CA	4AS	13BS	4CS
Economic Parameter	Change						
Baseline Economic Parameters	N/A	-3	-12.5	-6.9	-19.8	-32.4	-18.6
System Reliability	x1/10 *					-29.9	
Fuel Cell Cost	-10%	-1.7	-10.0	-4.7	-17.2	-28.2	-15.4
	-25%	1.0	- 6.1	-0.8	-13.2	-22.7	-10.8
Cost of Capital	-10%	-2.1	-10.7	-5.0	-18.0	-29.1	-15.6
	-25%	0.0	- 7.8	-1.8	-15.4	-25.0	-11.5
Electric Escalation Cost	+10%	-3.3	-12.4	-6.9	-19.4	-31.3	-18.0
	+25%	-2.9	-12.0	-6.6	-18.8	-30.7	-17.4

* Reliability is defined as hours of outage per 10,000 hours of operation. The baseline outage was 3 per 10,000 a reduction in reliability by 10 raises the outage to 30 hours per 10,000.

TABLE S-5

PERCENTAGE ANNUAL ENERGY COST SAVINGS

(Savings are Positive)

Component	Change	Residential	Store
Fuel Cell	Conventional Gas to Fuel Cell B	+ 51.3	+ 71.1
	From B to either C or A	- 15.4	- 21.9
Central Thermal Storage	0 to Optimum	+ .4	+ 1.9
	Eliminate Jacket Losses		0
Auxiliary Boiler	0 to Maximum*	- 5.1	- 33.8
	High Efficiency Modulating	+ 10.1	+ 1.8
Absorption Chiller	0 to 10% of Cooling Load	+ 0.6	+ 1.6
	Advanced Maximum Efficiency		+ 12.8
Battery Storage		+ 1.2	- 16.0

* 100% of cooling is met by the auxiliary boiler and absorption chiller.

TABLE S-6

PERCENTAGE SAVINGS IN LEVELIZED ANNUAL COST

Component	Change	Residential	Store
Fuel Cell	B to A or C	+ 8.7	+ 9.9
Central Thermal Storage	None to Optimum Size	+ 1.0	+ 3.4
	Eliminate Jacket Losses		+ 0.1
Auxiliary Boiler	0 to Maximum	- 7.3	- 14.1
	Standard to High Efficiency	- 1.0	+ 3.7
Absorption Chiller	% of Cooling Load 0 to 10%	- 2.8	+ 1.0
	% of Cooling Load 10 to 100%	- 4.9	- 6.4
Domestic Hot Water Storage	Double Size from 2 Hour Minimum	- 3.8	- .4
Heat Exchangers	Eliminate Hot Water Heat Exchanger	+ .003	+ .004
Battery Storage	0 to 1000KWH	+ 2.7	- 15.9
Automated Energy Management System	Reduce Peak Electric Demand	+ 5 to + 10 (Rough Estimate)	

1.4.2 Fuel Cell

Though its impact is dependent of the type of financing and ownership, the fuel cell power plant cost is the single most important component cost in determining the attractiveness of on-site fuel cell systems. The average (50KW) fuel cell power plant installed cost is between $16,000 and $23,000 ($300 per kilowatt) in the systems analyzed in this program. Today's prototype unit costs are estimated to be approximately 1,500 dollars per kilowatt representing a substantial challenge to reduce the fuel cell unit costs. Achieving the fuel cell power plant cost levels projected for the future should be considered a priority program goal. In addition, reducing the added operating and maintenance cost of $10,500 per year for the fuel cells would have a substantial effect on the annaul operating cost (about $50,000 per year) of the system, particularly when load leveling thermal or electric storage is employed which reduce the installation capacity requirements but raise the operating and maintenance cost which are based on developed KWH.

In general, Fuel Cell C (all steam, advanced technology) is preferred because of its lower cost and higher overall efficiency (Table S-7). However, it is limited to a 100KW module minimum and this is a distinct disadvantage in a stand-alone system where redundancy is required. Fuel Cell C also has the highest outage rate. These two factors combine to cause the systems with Fuel Cell C to require about 46% higher capacity than the other fuel cells in the apartment, which are available in more optimal 20KW modules. Fuel Cell A, the next lower cost type then becomes the best choice for the apartment which does not require steam for the chillers. We recommend further attention be given to the development of lower minimum module sizes for the advanced fuel cell when designed for stand-alone systems requiring redundancy and to lower the forced outage rate to that of the other fuel cells.

The disadvantage of large module sizes of Fuel Cell C is offset by the demand for steam in the retail store and unlike the apartment, Fuel Cell C is the choice for the retail store.

TABLE S-7

FUEL CELL CHARACTERISTICS

CHARACTERISTICS	TYPE A	TYPE B	TYPE C
Status	Near Term Technology	Current Technology	Advanced Technology
Minimum Module Size, KW	20	20	100
Maximum Module Size, KW	300	300	500
Maximum Delivered Water Temperature	98.9°C (210°F)	71°C (160°F)	-
Maximum Delivered Steam Pressure	-	515KPA (60 psig)	515KPA (60 psig)
Module Forced Outage Rate, Percent	3	3	5
O&M Cost, Mils/KW-HR	6	6	6
Module Cost Constant, C_0*	420	615	463
Cost, $/KW			
Minimum Module Size	340	503	336
Maximum Module Size	282	413	300
Full Load Efficiency, % LHV			
Total	83	75	84
Electrical	37	37	46

*Purchased Price $C = C_0 \cdot KW^{.93}$

Where C = Purchase Price (1978 Dollars)

KW = Module Size

C_0 = Tabulated Constant

Cooling fans are integral to the fuel cell and manage waste heat not used by the HVAC system. These fans and motors add cost to the fuel cell both as purchased parts and as they require additional cabinetry and mounting hardware. Based on our analysis we recommend that further studies consider eliminating a fraction of these cooling modules as they may be redundant with cooling tower capacity. During high thermal demand periods the cooling modules are idle and during low thermal demand periods there is probably spare HVAC cooling tower capacity to handle some of the fuel cell load.

1.4.3 Building Selection

Buildings such as the garden apartment with relatively high domestic water usage and flat load profiles are more conducive to stand-alone fuel cell applications than buildings such as the retail store which is dominated by high non-steady cooling demands. Other buildings such as:

- Hospitals
- Restaurants
- Fas Food Stores
- Central Kitchens
- Food Preparation Centers
- Factories
- Process Applications
- Food Processing Plants

may be even more attractive applications.

Selection of appropriate buildings for on-site fuel cell system should be predicated on the basis of the quantity and temperature of thermal energy and the steadiness of the thermal and electric loads. We recommend that a figure of merit be developed reflecting these measures of adaptability in fuel cell systems. The approach we recommend is to hypothesize generic load profiles that characterize major building types and test the system performance of the building in the system computer model. A series of thermal and electric relations can be developed which point to the best type of buildings for on-site fuel cell systems.

1.4.4 Thermal Storage

Large central thermal storage for space conditioning should be considered when the building load is dominated by a non-steady function such as space cooling. Though the store requires about twice the installed fuel cell capacity as the apartment, (about 700KW versus 400KW) the optimum size of thermal storage for the retail store is about 100 times greater than in the garden apartment due to the non-steady nature of the building load for systems without electric grid connection. The amount of thermal storage needed is likely to change if grid connection is provided.

This study clearly indicates that cool water thermal storage is preferred over high temperature storage for the absorption chillers independent of remainder of the system. Cool storage ($52,000) can reduce the absorption chiller capital cost in the store by about $36,000 and the fuel cell size by $38,710 saving a net of $23,000 of capital equipment.

Although improved thermal storage insulation would further reduce fuel consumption it would not appear to be an area needing attention. Fully eliminating thermal storage jacket losses for the large 378,540 liters has the effect of reducing the levelized annual cost.

1.4.5 Absorption Chillers

For nearly all of the systems considered in the retail store, an optimum partitioning of 10% absorption chiller capacity to 90% electric chiller capacity was indicated. This arises from the amount of waste heat available, the difference in chiller capital cost per ton and the large difference in COP between these two units.

No absorption chillers were indicated for the apartment. The available steam could be best used to meet the steady, high domestic hot water demand.

Improving absorption chiller efficiency at no change in cost will save between $17,000 to $34,000 in levelized annual cost (LAC). Achieving the higher COP levels of advanced absorption chillers will benefit fuel cell systems and is strongly encouraged.

A substantial part of the chiller cost is in the cooling tower and this cost could possibly be decreased slightly through system integration with the heat rejection equipment contained in the fuel cell. By judicious system design, the absorption chiller and fuel cell could share the same heat rejection cooling tower equipment and reduce installed costs.

1.4.6 Auxiliary Boilers and Air-to-Water Heat Pumps

Auxiliary boilers can reduce the levelized annual cost when there is substantial hot water or heating demand in excess of the thermal discharge of the fuel cell when meeting the base electric load. Operation of the auxiliary boiler to power an absorption chiller to displace electric demand for operating the electric chiller is not indicated to be cost effective. The problem with this approach lies in the capital cost of absorption chillers and not in the auxiliary boiler. The additional installed absorption chiller capacity to be powered by the auxiliary boiler and fuel cell is a substantial capital cost item and offsets the minor cost savings from reducing installed fuel cell capacity. Auxiliary boilers should be considered when there is a substantial heating demand beyond the thermal energy available from the fuel cell to meet the base electric plus chiller demands.

Air-to-water heat pumps were not included as a balance-of-plant component because it was felt that they offered no intrinsic advantage to the fuel cell based system and as such would benefit the conventional building equally. This argument can be justified in light of the effect of the auxiliary boiler on the system. The heat pump essentially offers a very high heating efficiency to both the conventional and fuel cell system. There is sufficient hot water and steam generated by the fuel cell for heating to make the heat pump energy savings contribution relatively insignificant. The primary function of the heat pump would be in the cooling mode where it would have to compete with a low cost high efficiency electric chiller supported by an absorption chiller sized to use waste heat from the fuel cell. Substituting a heat pump for an optimized electric/absorption chiller combination is likely to increase the levelized annual cost of the fuel cell based system and reduce the levelized annual cost of the conventional system. Confirmation of this argument should be undertaken as part of future studies.

1.4.7 Battery Storage

Battery storage (at $50 per KWH) for stand-alone on-site fuel cell systems offers a reduction in levelized annual cost. Some of the battery storage benefit is offset by the fixed charge (based on KWH output which is not reduced) for the operating and maintenance cost of the fuel cell. Though the net system capital cost reductions range from $9,000 to $36,000 (including the added $50,000 for battery storage), the fuel cell operating and maintenance (O/M) charge increases range from $1,765/year to $2,170/year based on the present technique for estimating fuel cell O/M costs as a function of delivered KWH. These charges should be changed to reflect the benefit of load leveling on operating/maintenance costs for the fuel cell.

If there is a necessity to maintain the stand-alone power plant feature (no electric grid connection) then battery storage integration with the fuel cell power plant should be considered. Efforts should be directed at developing shared electric control panels for the battery and fuel cell, and the effect of battery storage on fuel cell operating and maintenance costs should be examined. More refined battery installation costs should be developed for this specific application.

1.4.8 Automated Energy Management Systems

Automated Energy Management Systems (AEMS) should be considered for all fuel cell applications. Typically, an AEMS system will cost from \$5,000-\$30,000 depending on the number of devices it must control, and it will provide:

- Peak load shedding
- Optimal start/stop of HVAC equipment
- Enthalpy controlled ventilation

The peak load shedding is done on a predetermined priority use basis and can substantially reduce the peak electric demand. A conventional HVAC system would benefit from load shedding by reducing the demand charge but the net savings would probably not be as much as the on-site fuel cell system. In this study, no demand charge was made against the conventional system and the net effect of an AEMS would be the substantial capital cost savings to the fuel cell system, as the conventional and fuel cell systems would probably benefit equally from the optimal start/stop and enthalpy control functions. If the AEMS system could limit the apartment to a 200KW base load (System 8AA) a \$68,000 savings in fuel cells could be achieved.

We recommend that a study be conducted with AEMS/fuel cell systems accounting for the demand charge on the conventional systems. We regard this as a high priority recommendation as it could substantially improve relative fuel cell economics.

1.5 Business and Policy Recommendations

1.5.1 Ownership and Financing

Power plant ownership is a central question to the future of fuel cell utilization. Ownership could be in the hands of a number of entities not limited to the following:

- Gas and/or Electric Utility
- Building Owner (if not the Developer)

- Developer
- Separate Leasing Corporation

The ownership will effect many of the aspects of the system including the issue of utility grid connection and financing of the power plant as discussed in this and the following section.

1.5.2 Utility Ownership

The fuel cell power plant could be owned by the local gas or electric utility and along with potential benefits a number of complex issues arise. The TARGET (Team to Advance Gas Energy Transformation) project identified gas utility ownership as the superior ownership alternative.

Utility ownership may broaden the financing options to the builder and would certainly lower the capital investment requirement of the building owner. The utility would gain revenues from the operating and maintenance as the rental income of the equipment. However, these advantages may be offset by other business considerations:

- Electric grid backup
- Revenues to the builder (5.3.3)

Gas utility power plant ownership makes electric grid connection backup arrangements unclear. The public policy and financial user implications of such an arrangement should be investigated.

A grid connected electric utility owned fuel cell power plant concept was examined by Westinghouse [Reference 11] in which 10 different strategies for load shedding were considered. Their findings indicate that a grid connected fuel cell system will benefit the electric utility if on-site generating strategies are employed that improve the utility load factor.

Alternatively the utility could retain ownership of the fuel cell and lease it to the developer. In this arrangement the developer could benefit from the control of the power plant but would not take the same level of risks (see Section 1.5.4 - Risks) as an owner. One area of concern to the developer is the long-term availability of natural gas needed for the fuel cell. The uncertainty of natural gas supply and cost coupled with future regulations setting the priority of gas users makes an investment in the fuel cell a high risk undertaking. Innovative leasing arrangements could abate some of these risks.

1.5.3 Developer Ownership

The developer could own the power plant (the fuel cell modules cost less than 30% of the HVAC capital cost and are a much smaller fraction of the entire building project) and work the operating cost and capital charge into the rent basis of the building. The developer would assess the cost of the plant, add a profit and compare this charge to the local electric utility charge. If the fuel cell cost plus overhead and profit are competitive then this would be part of the advertised rent base when space is being sold. While the developer must perform the financial analysis, a reliable and relevant set of financial data must be made available. This should be a principle function of future fuel cell development work.

1.5.4 Risks

The developer views the risk of a fuel cell based power plant in its effect on the entire building project. If the fuel cell fails it would threaten the entire project affecting tens of millions of investment dollars. Until the fuel cell is shown by demonstration to be totally reliable a developer would require a complete backup capability - full power grid connection. This would greatly reduce the attractiveness of the system since the utility would charge a substantial monthly standby charge to the project.

Increased liability insurance could result from the fuel cell installation even if the fuel cell is technically as safe as a conventional boiler. The increased cost comes from the limited historical experience with fuel cell installations which is likely to cause insurance companies to view the equipment as a higher than normal risk.

Another risk identified earlier is the availability of fuel. This can be somewhat mitigated as the multi-fuel capability of the fuel cell is expanded. However, in the near term, the dependence on natural gas raises the risk of supply interruption.

Finally, developers are exposed to the risk of not negotiating satisfactory electric grid backup with electric utilities that are not also providing the natural gas.

1.5.5 DOE Policy

The Department of Energy policy regarding 40KW on-site fuel cell systems will have a direct bearing on most of the issues identified. The questions of fuel cell development and balance-of-plant component development can be accelerated with DOE involvement and sponsorship of programs. Fuel cell ownership, particularly with utility ownership, will involve DOE regulatory decisions of considerable importance. Government tax incentives could make private ownership of fuel cell power plants more inviting to the developer or building owner. Government support to utilities or private companies that would own and operate the power plants for the building owner should also be considered. These areas will require additional analysis before a firm policy recommendation could be developed for DOE.

DOE should establish a clear, long term fuel supply scenario for the fuel cell. The first generation fuel cell will be based on high priority natural gas which is likely to cause any investor great concern. Commercial building developers have confronted the complex and volatile issue of natural gas availability for a number of years and are reluctant to make large capital investments in equipment with a 30 year lifetime which is dependent on a specific fuel source with an uncertain future.

DOE must offer the investor a reasonable level of security that fuels adequate to power the fuel cell will be available for the near future.

Lastly, a field demonstration of 10 to 100 large projects using on-site fuel cell is needed. A developer or investor requires proven reliability and fuel cost savings before they would support a fuel cell installation.

1.6 Summary Recommendations

The following section highlights the key technical, financial and policy recommendations derived in this study. Most of these recommendations are discussed in detail in the foregoing section, some are corollaries or extensions and are presented without further development.

Fuel Cells

- Concentrate on the development of accurate installed cost projections for the fuel cells.

- Develop cost saving designs by sharing housing facilities, controls and cooling towers with the BOP components.

- Continue to develop advanced steam source fuel cells and target lower minimum module size (to the 20KW level) for application in stand-alone systems requiring redundancy.

Building Selection

- Examine internal rate of return for fuel cell systems in a number of building types in different climatic zones.

- Develop a figure of merit reflecting: building thermal to electric load ratio and steadiness of load for use in selecting appropriate sites for fuel cells.

Auxiliary Boilers

- Auxiliary boilers are not indicated as beneficial for any system.

Automated Energy Management Systems (AEMS)

- Conduct a study with an AEMS/fuel cell system in comparison with a standard building with an AEMS unit.

Battery Electric Storage

- For stand-alone systems requiring reliability comparable to grid connected system, battery storage may be beneficial. More accurate battery/system costs should be developed.

Heat Pumps

- As air-to-water heat pumps gain in market acceptance and become an accepted element of standard building, HVAC systems, the air-to-water heat pump should be factored into the fuel cell system.

- Evaluate the comparative levelized annual cost of air-to-water heat pumps for both fuel cell and conventional systems.

Thermal Storage

- Thermal storage for domestic hot water is necessary and can be met with minimal volume.

- Large central cool storage should be considered for all buildings dominated by the cooling load. Hot storage (pressurized) for absorption cooling is not recommended.

- Techniques for properly sizing thermal storage should be developed.

- Improved insulation technology is not necessary.

Absorption Chillers

- Extreme care should be given to the proper sizing of the absorption chillers - electric chillers ratio.

- Develop high efficiency absorption chillers (1.8 KW/ton).

- Absorption chillers are not recommended for all systems. Apartment cooling loads are best met with electric chillers only.

Fuel Cell Ownership

- Develop meaningful financial criteria to determine the desirable ownership strategy based on real building developer/builder business goals.

- Develop cost/benefit analysis of different ownership scenarios with and without electric utility grid connection.

Financing Recommendations

- Focus efforts on qualifying fuel cell system for conventional commercial loans at or near the prime rate (less than 15%).

- Develop grid connected system economics considering:
  - fuel cell redundancy
  - full backup

- Evaluate cash flow in several locations using local gas and electric rates and develop a system portfolio designed for the building developer.

- Develop consistent and credible fuel cell installed costs.

2. BACKGROUND AND PURPOSE

2.1 Benefits

Fuel cells, like other on-site power generation systems offer the potential for substantial energy conservation. Fuel cell power plants electrochemically convert fuel such as pipeline gas, coal gas, or liquid gas directly into electricity and heat. The fuel cell consists of three major subsystems: a fuel processor to clean and convert the fuel to hydrogen and carbon dioxide, a cell stack to electrochemically convert hydrogen and oxygen to direct current electricity, and an inverter to change this electricity to alternating current. By eliminating some distribution and transmission losses the fuel cell may deliver electric power at a higher net efficiency than central power stations. More importantly, waste heat from the electric power generation can be used on-site for comfort conditioning of the building substantially improving the energy utilization of the fuel cell.

Prototype and demonstration work on fuel cells has concentrated on using natural gas as the primary fuel though the fuel cell has a multi-fuel capability. Coal derived gaseous and liquid fueld (including methanol) look promising and usage, therefore, like the central power plant, the on-site fuel cell power system has fuel switching capability and therefore offers additional advantages to the nation.

2.2 Past Design Work

Most* of the on-site fuel cell power systems work to date has been conducted by the United Technologies Corporation under sponsorship of the gas utilities in the TARGET (Team to Advance Gas Energy Transformation) Program. In that study 35 test sites were equipped with 12.5KW fuel cell power plants. [Ref.1] Attention was given to the annual performance and maintenance and the on-site fuel cell system. Deficiencies in fuel cell power plants were identified. Little attention was given to optimizing the HVAC equipment to the fuel cell characteristics on a building-by-building basis.

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* A 4KW experimental fuel cell power plant was tested by Columbia Gas Systems in 1966 prior to the TARGET program.

A new field test to establish operational feasibilility is presently underway. With GRI/DOE in sponsorship, utilities are participating in the planned test of about 50 power plants (each 40KW) in about 25 sites.

Resource Planning Associates, under contract to GRI and Oak Ridge National Laboratories assessed the market potential of on-site fuel cell power systems and examined the performance of fuel cells in a variety of buildings. The simulations did not consider the alternative system performance and capital cost of optimizing heating, ventilation and air conditioning equipment to match the fuel cell performance to the specific buildings under consideration. A similar study by Mathtech was conducted identifying two specific buildings for fuel cell analysis. The Mathtech Study examined three types of fuel cells and their characteristics in the building energy systems.

Under contract to NASA-Lewis, Westinghouse Electric Corporation has studied the effects of utility grid connection on the cost effectiveness of on-site fuel cell power systems in specific building applications. Their findings show enhanced annual performance with grid connection.

Key elements of past work on on-site fuel cell power systems for residential and commercial buildings can be characterized as follows:

- Fixed HVAC equipment - studies concentrated on the effect of other system characteristics than the HVAC design to match the fuel cell to the building.

- Fixed building - building type selected for optimal fuel cell-HVAC system design.

- Fixed fuel cell - studies centered on a single fuel cell type.

- Performance - system performance analyzed without estimation of the capital cost and payback. (An economic evaluation was performed by Arthur D. Little for NASA [Ref.3] on Industrial Applications of Fuel Cells).

2.3 Purpose and Scope of Work

The purpose of this study is to evaluate the impact of available and soon-to-be-available heating, ventilation and air conditioning components on the performance and cost of on-site integrated fuel cell systems, and to identify policy and technical alternatives that could improve the economics and competitive posture of these systems. To accomplish this, a program was developed under contract to NASA with the principal tasks shown schematically in Figure 1.

Arthur D. Little was the prime contractor with: R. G. Vanderweil Engineers and Urban Investment and Development Company serving as subcontractors. Vanderweil developed the HVAC component data base and supported the system definition work. Urban Investment guided the financial analysis and provided insights into the commercialization of fuel cells from the developer viewpoint. Urban Investment is a large commercial building developer with assets in excess of $800 million dollars. R. G. Vanderweil is a well known mechanical engineering firm with years of HVAC design experience.

In Task 1, a component data base (Volume II) detailing the thermal performance and cost of common heating, cooling, ventilation, piping and control systems for multi-family residential and commercial buildings was developed. The data was compiled in a form that could be used in a computer program also developed in Task 1. The computer model allows for a variety of system configurations and component sizes and will operate the components to meet a given building thermal and electric load. In addition, the computer model estimates the capital cost, maintenance and operating costs, and performs financial analyses of the economic data.

In Task 2, some 108 system concepts were identified and analyzed with the computer model. System schematics of those having the lowest annual system cost were identified in Task 3 and an economic analysis of the various systems was performed in Task 4 using levelized annual cost and discounted cash flow parameters. The economic analysis was based on a comparison of fuel cell based systems with conventional gas and electric systems.

In Task 5 and 6, custom components (non-standard component sizes), and advanced components (high-efficiency components likely to be available in the near future) were identified and integrated into the system.

2.4 Relationship to Other Programs

This study provides an analysis of three types of fuel cells in more than 100 integration schemes in two buildings. Strategies for optimizing the system design to reduce annualized cost are developed. System economics from the viewpoint of a building developer were examined and recommendations for enhancing the attractiveness of fuel cell systems are made.

This study represents a critical link in the commercialization of on-site fuel cell systems because it focusses on the issue of accelerating the acceptance of these systems through design and policy alternatives. Figure 2 summarizes the central function this analysis serves in the continuum or programs designed to bring on-site fuel cell total energy systems into widespread use. We believe that the findings of this study and future updates of it will be help map necessary future demonstration and market assessment pro-rams of fuel cell systems to accomplish the goal of successful commercialization.

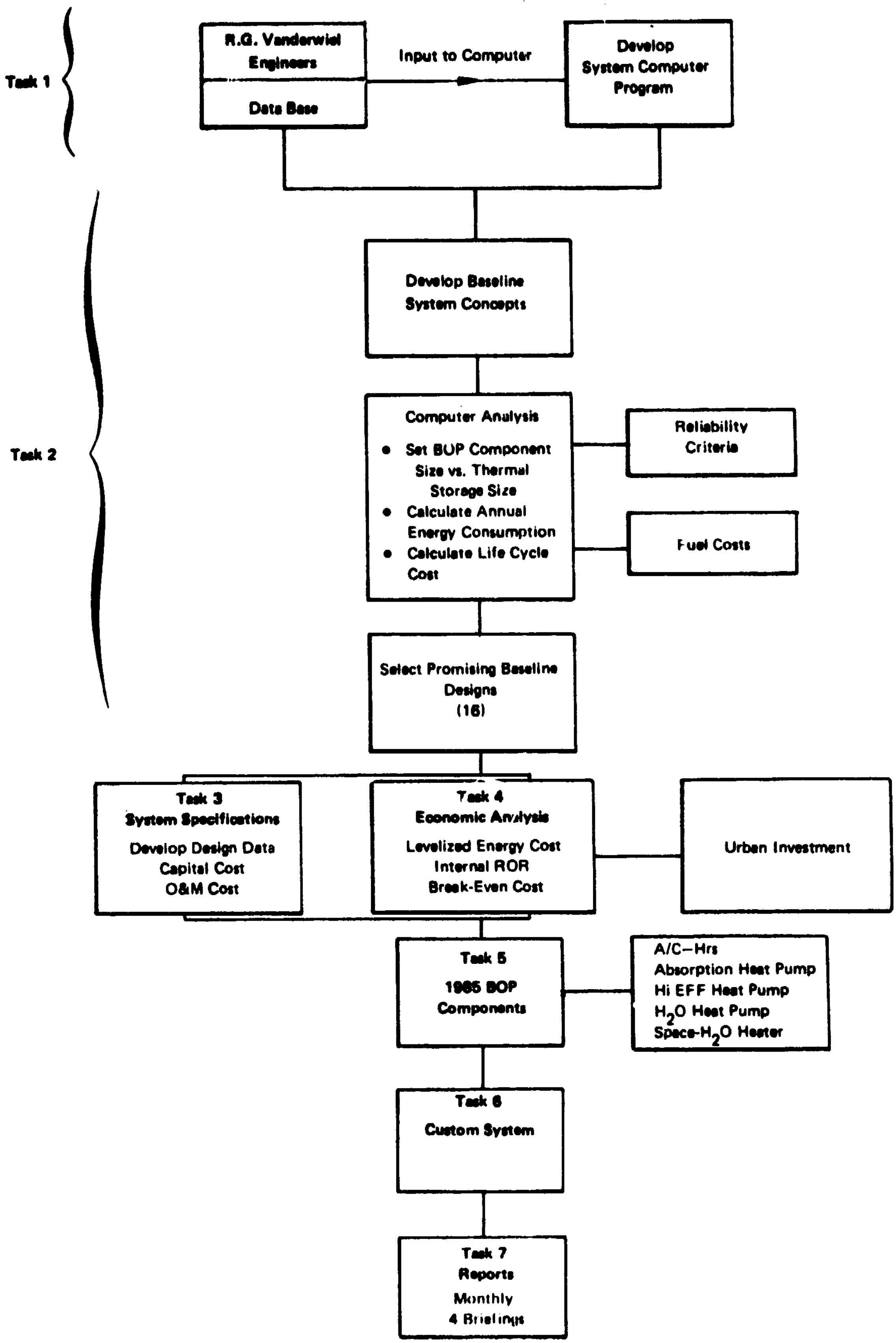


FIGURE 1 **OVERVIEW OF PROGRAM METHODOLOGY**

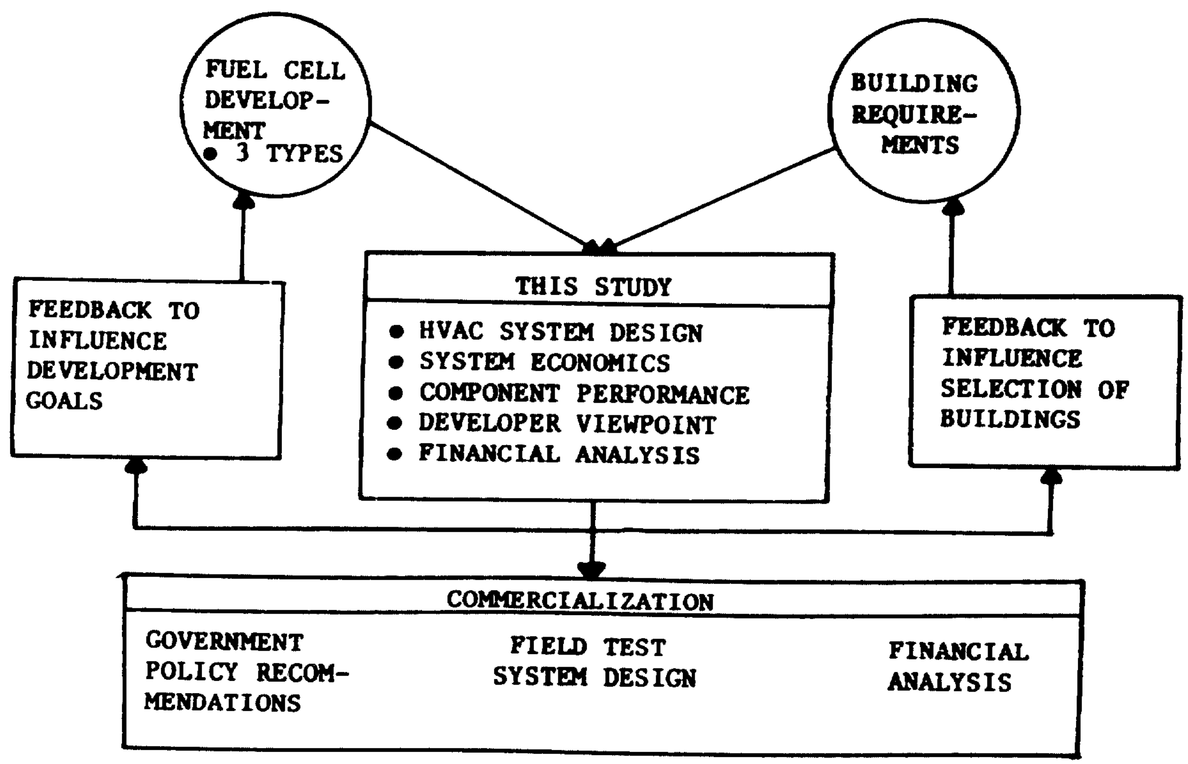


FIGURE 2

RELATIONSHIP OF THIS STUDY TO COMMERCIALIZATION OF ON-SITE FUEL CELL SYSTEMS

3. BUILDING AND FUEL CELLS SELECTED FOR STUDY

3.1 Description of Buildings

Two buildings were identified by NASA Lewis for this study of fuel cell integration systems concepts. A retail store of 112,163 square feet and a 96-unit apartment complex were identified. The key characteristics of these two buildings are given in Tables 1 and 2. These specifications along with other details on the floor plan, window area and domestic water usage were used as input to a well established building load program to develop the building load profile for the apartment. Building load data for the store was provided to ADL by NASA Lewis.

Garden Apartment Computer Model

The garden apartment complex consists of four identical 24-unit buildings each oriented with major axis east and west. Each 24-unit apartment building is divided into twelve spaces or zones, six per floor. On each floor, the four corner apartments are designated as separate spaces. The four intervening apartments on each side of the building comprise the remaining two spaces. Since the end spaces with the same orientation have very similar thermal behavior, they are combined into the same heating and cooling system. The building is divided into eight systems.

The ESP-I program developed by Automated Procedures for Engineering Consultants (APEC), was used to develop hourly load profiles. The program uses ASHRAE response factor data to account for the heat storage capacity of the entire building in the hourly simulation. The output for each of the eight HVAC systems, in MBTU, is given for every hour of the year. Heating energy is positive, cooling energy is negative. Each system output represents the sum of the energy requirements of the four equivalent spaces in the four apartment buildings.

TABLE 1

RETAIL STORE DESCRIPTION

WASHINGTON, D.C.

	Retail Store	
Building Dimensions, M (FT)	93.6 x 111.3 (307 x 365-1/4)	
U-factors, W/M^2-°C (BTU/HR-Deg F-SF)		
Glass	3.4	(0.600)
Wall	1.2	(0.214)
Roof	0.51	(0.090)
Total Exposure Areas, M^2 (SF)		
Glass	167	(1801)
Wall	2514	(27063)
Roof	10420	(112163)
Number of Floors	1	-
Floor Area, M^2 (SF)	10240	(112163)
Ceiling Height, M (FT)	3.0	(10)
Maximum Occupancy	2664	-

TABLE 2

APARTMENT BUILDING DETAILS
(DATA FOR 1 OF THE 4 BUILDINGS IN THE COMPLEX)

Overall Building Dimensions	12.2M x 78.1M (40 ft. x 256-1/4 ft.)

Building Average U-Factors:

	W/M^2-°C	(BTU/HR-Deg F-SF)
Window	4.3	(0.750)
Wall	0.567	(0.100)
Roof	0.284	(0.050)

Roof Area	$952M^2$	(10248. SF)
Floor Area	$1904M^2$	(20496. SF)
Floor-to-Ceiling Height	2.43M	(8. FT)

Wall Number	Exposure Area M^2	Exposure Area SF	Glass/Wall Ratio %
1	406	(4368.)	20.
2	65.5	(705.)	0.
3	406	(4368.)	20.
4	65.5	(705.)	0.

Minimum Occupancy 72 people

Infiltration, Air Changes/Hour 0.8

The hourly domestic hot water usage was provided by NASA and amounted to 405 liters (107 gallons) of 27°C (80°F) rise hot water per day per apartment. A sample of the average day load profile is given in Figure 3.

Retail Store Load Profile

The retail store has characteristics shown in Table 1. Load profile data supplied by NASA-Lewis were used without alteration in the assessment of the integrated fuel cell systems in the retail store. A sample of the average day load profile is given in Figure 4.

3.2 Conventional HVAC Systems

Four conventional systems were developed. A gas and electric based HVAC system were identified for both the retail store and the garden apartment.

Four central air handling units were used in the retail store and cabinet-unit heaters and fan-coil units were used on the perimeter. An electric chiller and cooling tower were used along with required space heating and hot water boilers. An electric boiler was used in one system and a gas-fired unit in another. Figure 5 shows the electric based retail store conventional system and Figure 6 shows the gas-fired equivalent system.

A central plant for providing hot water and chilled water to the garden apartments was designed for the garden apartment application. Individual fan-coil units were located in each of the rooms of the garden apartment. Both a gas and electric based system were designed and these are shown in Figures 7 and 8, respectively.

FIGURE 3

RESIDENTIAL

AVERAGE DAY LOAD PROFILE

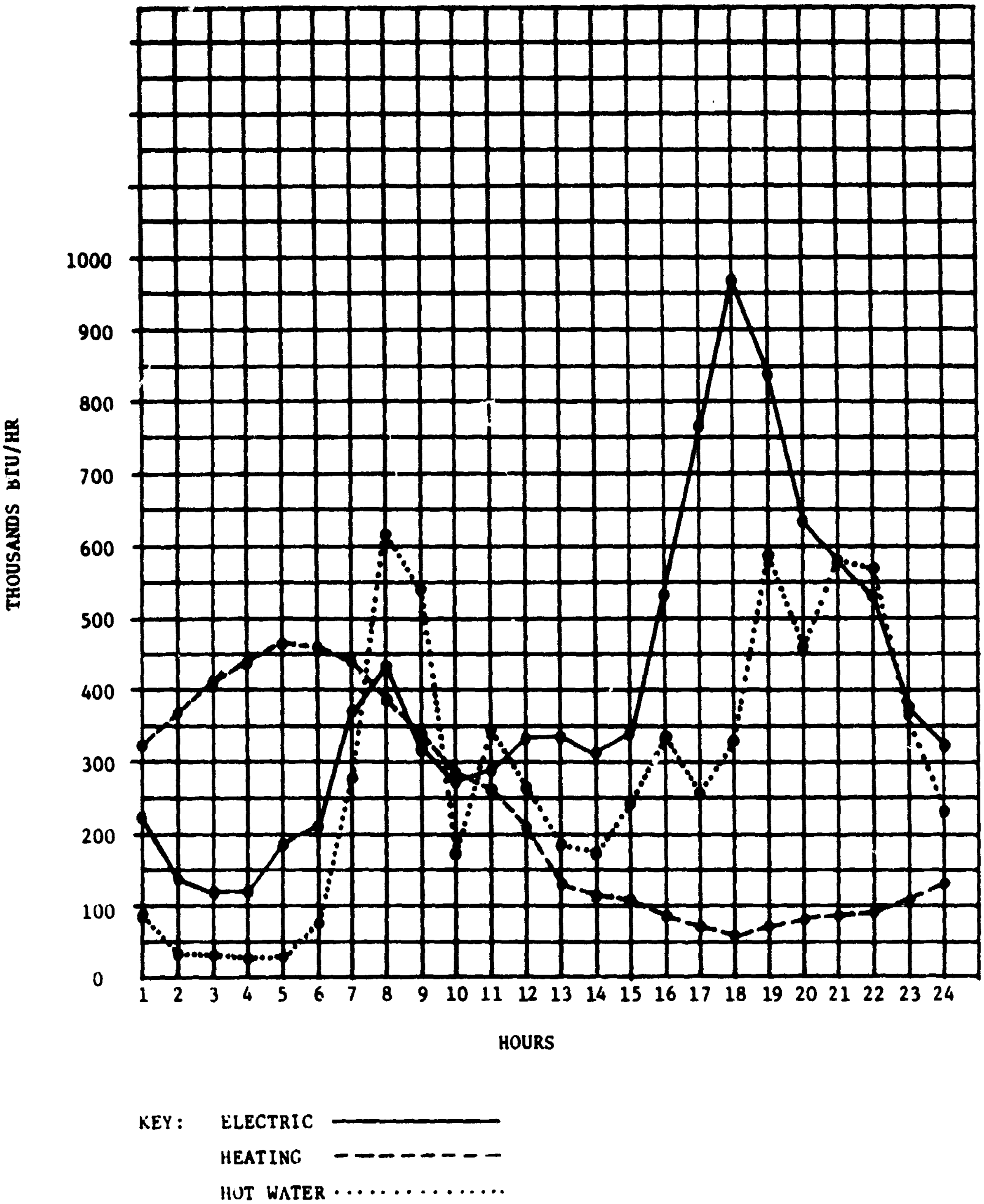
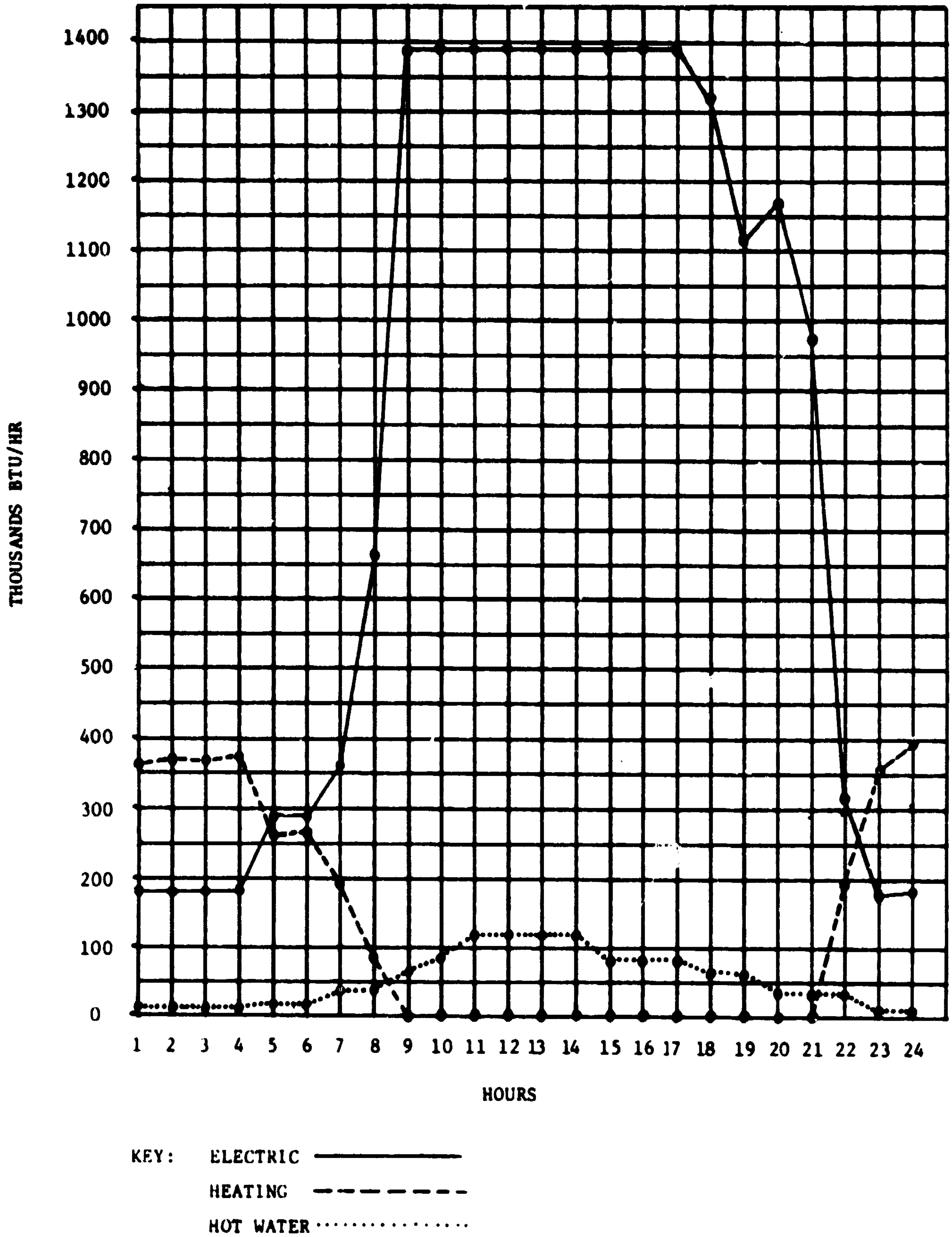
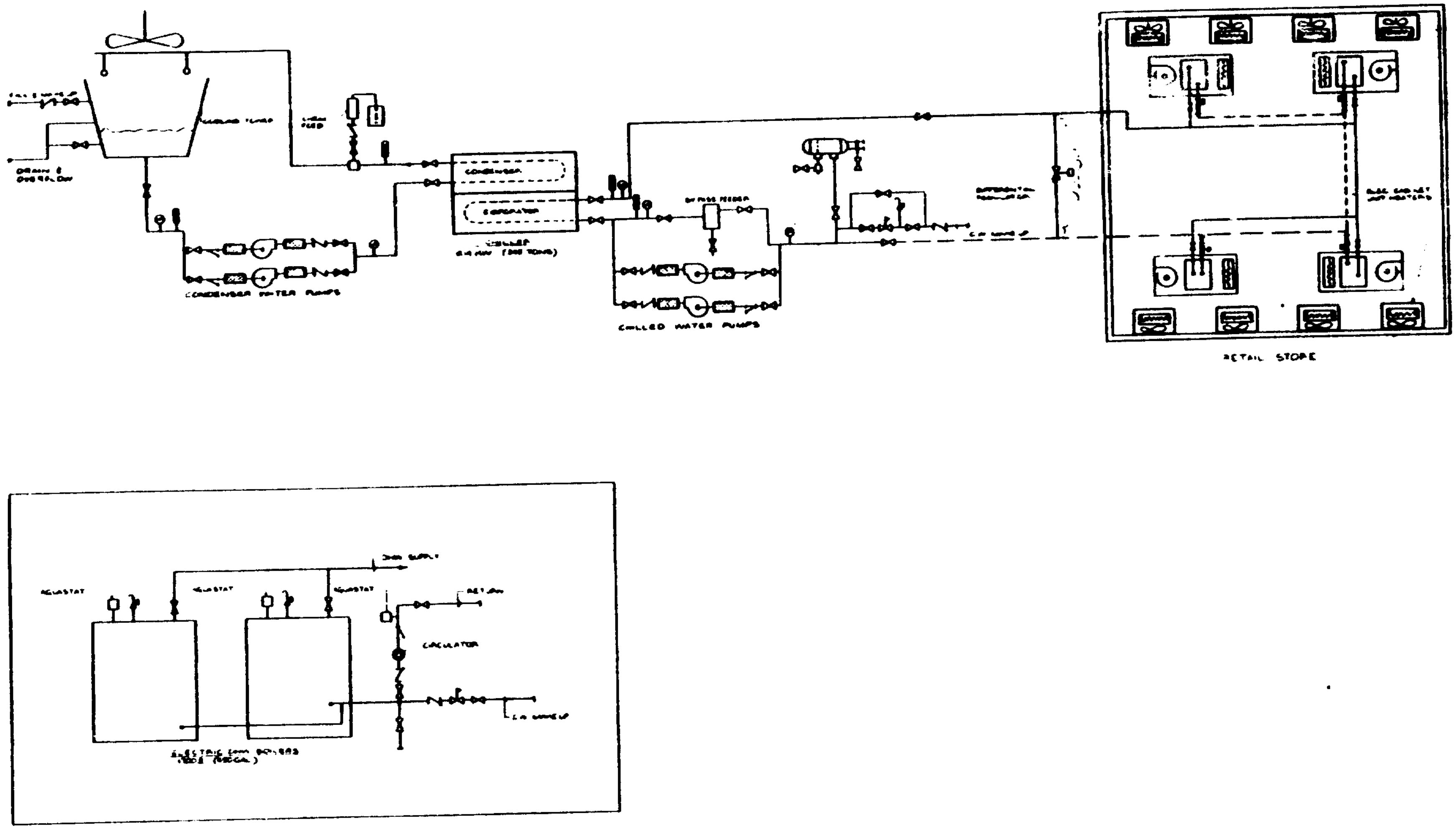


FIGURE 4

RETAIL STORE

AVERAGE DAY LOAD PROFILE





CONVENTIONAL
ELEC.
#2S

FIGURE 5

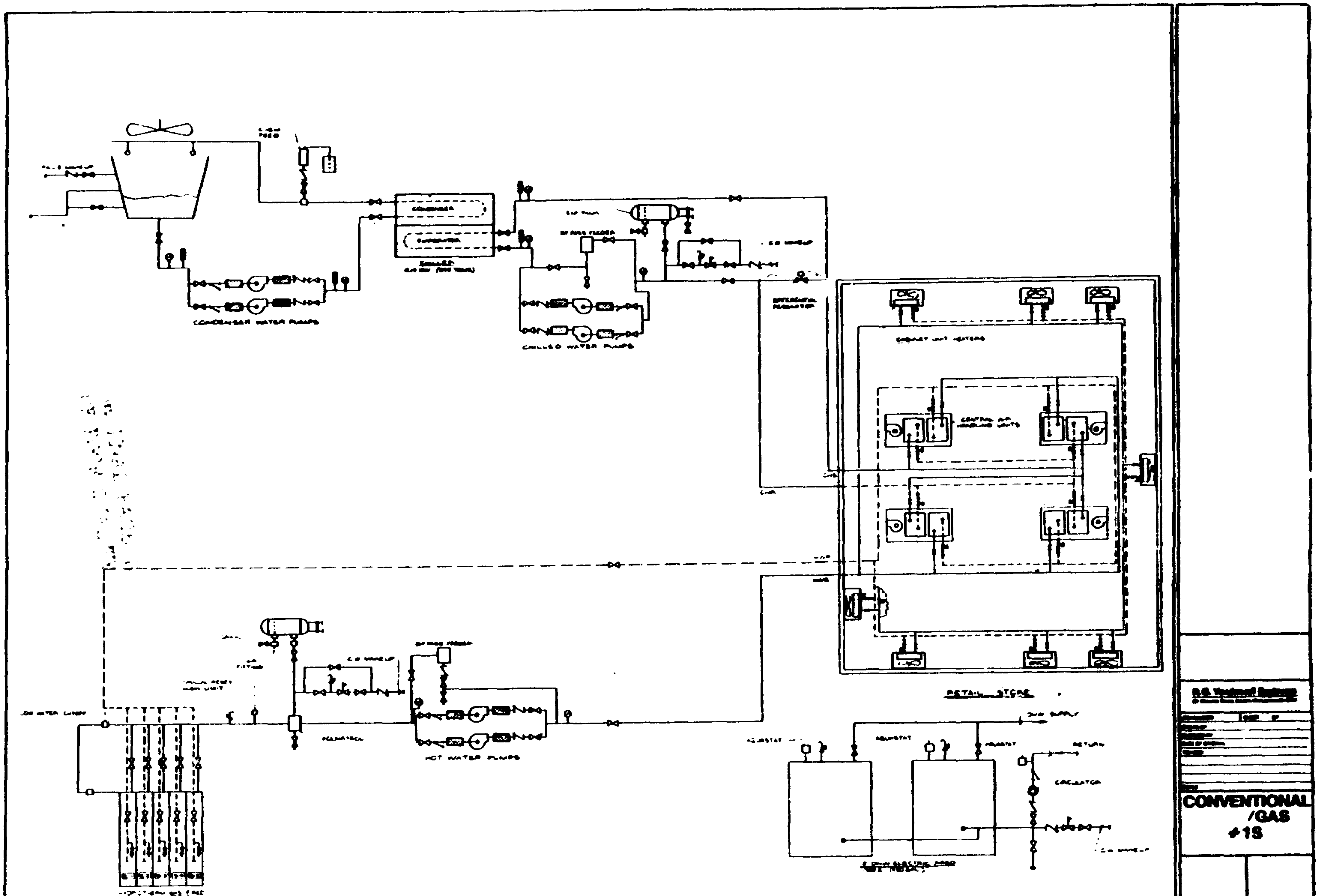
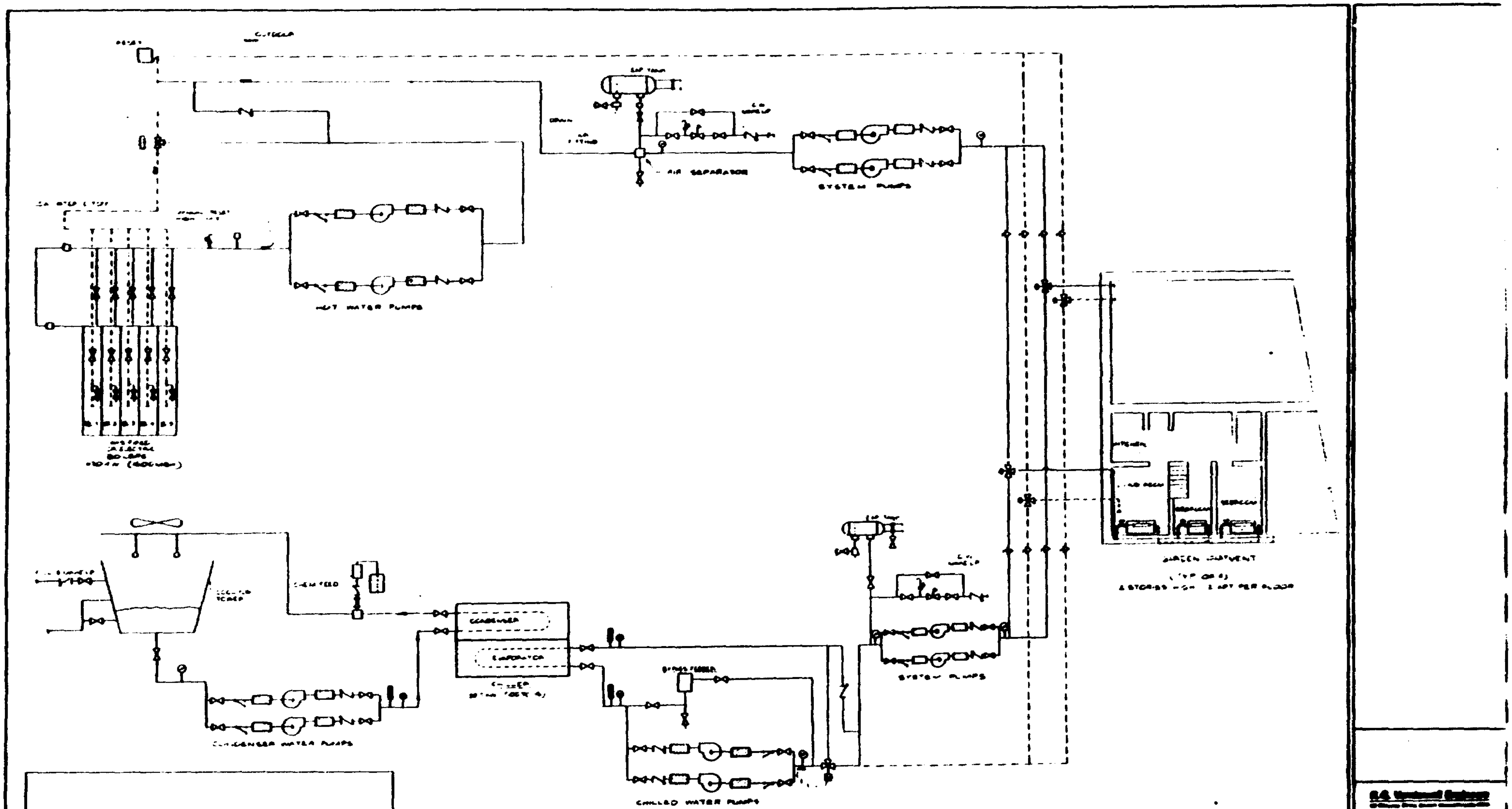

CONDENSER WATER PUMPS
CHILLED WATER PUMPS
HOT WATER PUMPS
CABINET UNIT HEATERS
CENTRAL AIR HANDLING UNITS
RETAIL STORE
AQUASTAT
DHW SUPPLY
RETURN
CIRCULATOR
CONVENTIONAL /GAS #1S

FIGURE 6



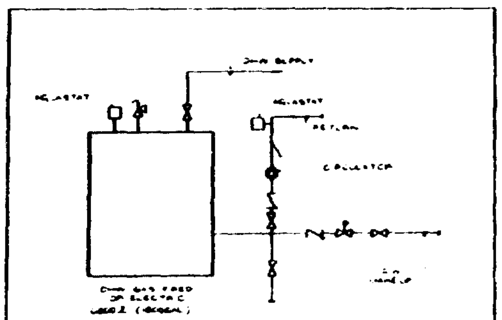


FIGURE 8

FIGURE 7

3.3 Performance and Cost of Fuel Cell Designs

Three fuel cell types were used in this study. The performance characteristics of each fuel cell under variable load and cost data were provided by NASA-Lewis. For the purposes of this study the fuel cells were characterized as follows:

Type A - air-cooled fuel cell, near term technology (1985)

Type B - liquid-cooled fuel cell, present technology

Type C - liquid-cooled, advanced technology fuel cell

Type B and A power plants are representative of those being developed for commercialization in the 1985 timeframe while Fuel Cell C represents advanced technology. The complete fuel cell descriptions provided by NASA-Lewis including physical and operational characteristics are reproduced in Volume II, Section 1.2.

A fuel cell power plant consists of a fuel processor, a fuel cell power unit, an electrical inverter, a cooling system, and a heat recovery system. Liquid-cooled fuel cells have two sources of recoverable thermal energy: 1) the recirculating liquid coolant loop which can be used to raise steam, hot water, heated air, or some combination of all three; and 2) the reformer and cathode vents which can be used to generate hot water or heated air. [Ref.3].

The air-cooled fuel-cool also has two sources of recoverable thermal energy: 1) the recirculating air coolant which can be used to generate hot water or heated air, and 2) the reformer and cathode vents which can be used to generate hot water or heated air. For the purpose of this study it was assumed that fuel cell modules with all the heat recovery options described above are available and that the fuel cell capital cost is unaffected by the type of heat recovery system assumed.

The recovery of thermal energy from the heat recovery system is entirely optional and does not affect the fuel cell system operation. Heat which cannot be recovered by the heat recovery system or heat from the heat recovery system that is not utilized, is automatically removed by the cooling system. The cooling fan is included in the module.

The key characteristics of the three fuel cells are summarized in Table 3.

An estimate of the installation cost of the fuel cell was made by analogy with an absorption chiller which shared most of the same interconnection requirements as a fuel cell of equal size. A 352KW (100 ton) absorption chiller and a 50KW fuel cell were used in the comparison.

	FUEL CELL	ABSORPTION CHILLER
Weight	3856KG(8500 lbs)	5257KG(11,590 lbs)
Slab Size	6.0 Sq.M.(65 Ft^2)	6.2 Sq.M.(67 Ft^2)

The installed cost of the chiller is:

Labor $25/Hour x 85 Hours [Ref.4]	=	$2,125
Concrete and Forms		259
TOTAL		$2,384

or about $50 per KW of the fuel cell.

TABLE 3

FUEL CELL CHARACTERISTICS

CHARACTERISTICS	TYPE A	TYPE B	TYPE C
Status	Near Term Technology	Current Technology	Advanced Technology
Minimum Module Size, KW	20	20	100
Maximum Module Size, KW	300	300	500
Maximum Delivered Water Temperature	98.9°C (210°F)	71°C (160°F)	--
Maximum Delivered Steam Pressure	-	515KPA (60 psig)	515KPA (60 psig)
Module Forced Outage Rate, Percent	3	3	5
O&M Cost, Mils/KW-HR	6	6	6
Module Cost Constant, C_0*	420	615	463
Cost, $/KW			
Minimum Module Size	340	503	336
Maximum Module Size	282	413	300
Full Load Efficiency, % LHV			
Total	83	75	84
Electrical	37	37	46

*Purchased Price $C = C_0 \cdot KW^{.93}$

Where C = Purchase Price (1978 Dollars)

KW = Module Size

C_0 = Tabulated Constant

4. INTEGRATED SYSTEM DESIGN AND ANALYSIS

4.1 Computer Model

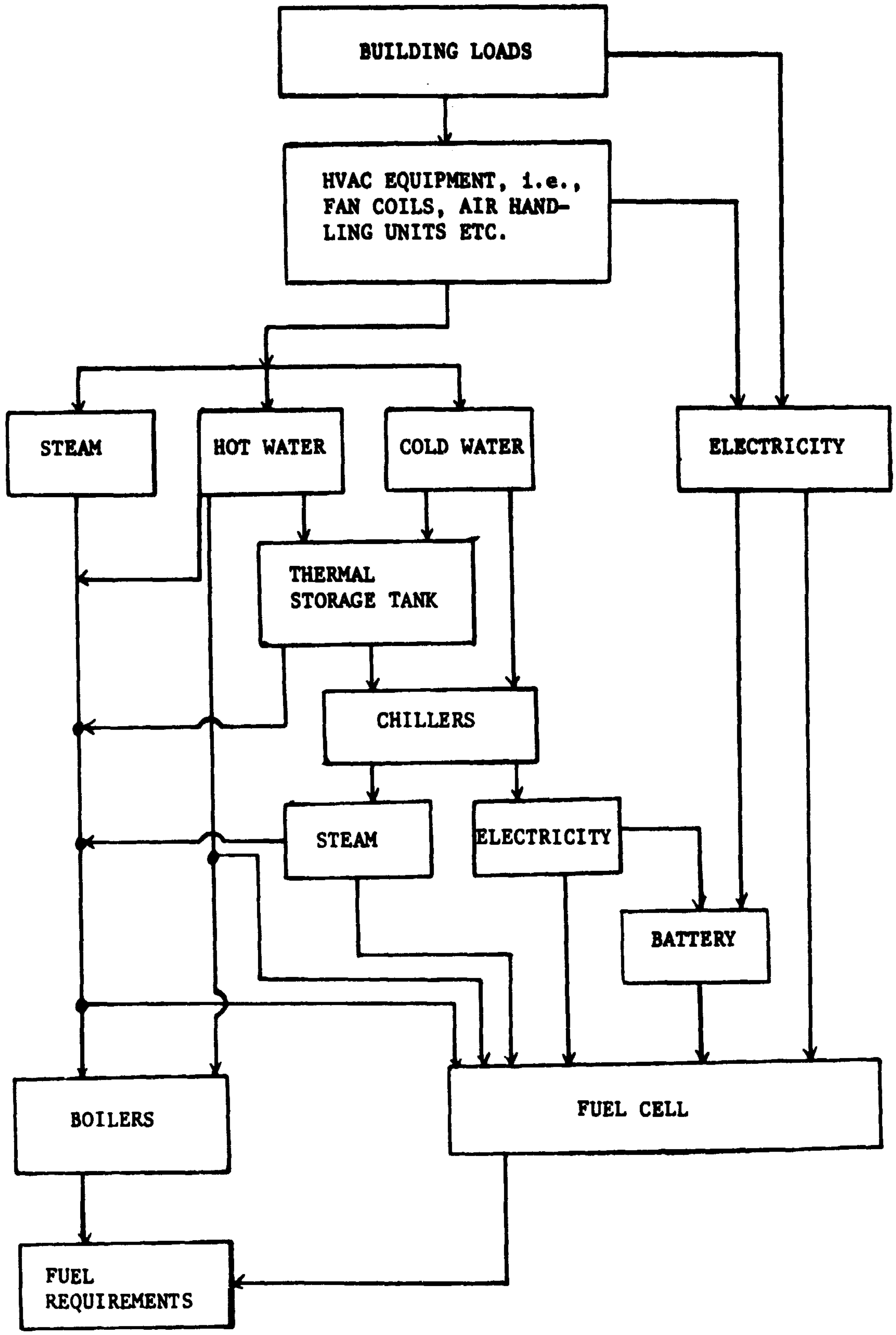
A Fortran computer model written for an IBM 370 computer was developed in this project to simulate a variety of system designs over the annual operating cycle of the building. The program was designed to allow the user to input the broadest possible spectrum of fuel cell and HVAC equipment. The model (see Figure 9) was designed to treat a wide variety of system configurations that go well beyond the scope of those examined in this study.

To allow a wide variety of systems to be treated, the program is in a modular form. A module may be a boiler, or a fuel cell or a thermal storage tank or any other piece of HVAC equipment. The user then specifies what modules are to be a part of the complete HVAC system. In a real HVAC system all the components would be operating simultaneously. In the model however, the user must operate the components in series. This results in slightly different energy flow predictions. For example, if the non-HVAC building electricity load is 90KW, a 100KW fuel cell would operate at 90% load to meet this demand. Simultaneously, some 2KW pumps may be circulating byproduct fuel cell hot water to the heating system heat exchanger. In the first pass through the model the 2KW for the pumps will not be accounted for since the fuel cell byproduct hot water is calculated last. To correct for this error, the model uses the updated HVAC demands and recalculates the hourly system performance. For practical purposes the model only recalculates the HVAC demands once, since the impact of the HVAC system on the overall load is relatively small. This process is repeated hourly until the entire day has been completed. The program then prints the daily energy flows for each HVAC module.

Normally, only a few days are selected to represent an entire year. When a seasonal change from heating to cooling (or vice versa) occurs the hot storage tank becomes a cold storage tank. The model assumes that the storage tank seasonal changeover requires no additional energy. The

FIGURE 9

COMPUTER MODEL ENERGY FLOW



real system would require very little energy on a yearly basis for seasonal changeover for the following two reasons. First, a real system would anticipate a seasonal changeover and deplete the storage tank prior to the end of the season minimizing the energy required for the changeover. Second, there are only two changeovers per 365 days, thus the impact on the yearly energy usage is negligible.

Once all the days have been modeled, the yearly results are obtained by scaling the results up to 365 days.

The fuel cell may be any size, so the model, by trial and error, calculates the size that results in a minimum overall fuel cell capital cost. The Levelized Annual Cost and cash flows are then performed.

Figures 9A through 9J show the overall program logic and the logic for the systems employed in this study.

Beginning with the requirements of the building for heating or cooling, hot water, and electricity for lights and other non-HVAC equipment, three basic forms of energy: 1) steam, 2) hot water, and 3) electricity are used to meet the load. Each energy flow is treated independently. The steam requirement results from hot water needs and the absorption chiller; steam is supplied by either the boilers, the fuel cell, or both.

The hot water requirement results from domestic hot water needs, heating equipment loads, and the thermal storage recharge schedule. The hot water is supplied by some combination of the following: thermal storage discharge, boilers, fuel cell.

The electricity requirement results from lights and other non-HVAC equipment, as well as HVAC pumps and fans, and the charge cycle of the battery storage if used. The cooling load from either the building or the thermal storage indirectly results in electrical demands, in that a centrifugal or a reciprocating chiller is required. These electrical requirements are met by battery discharge and/or the fuel cell.

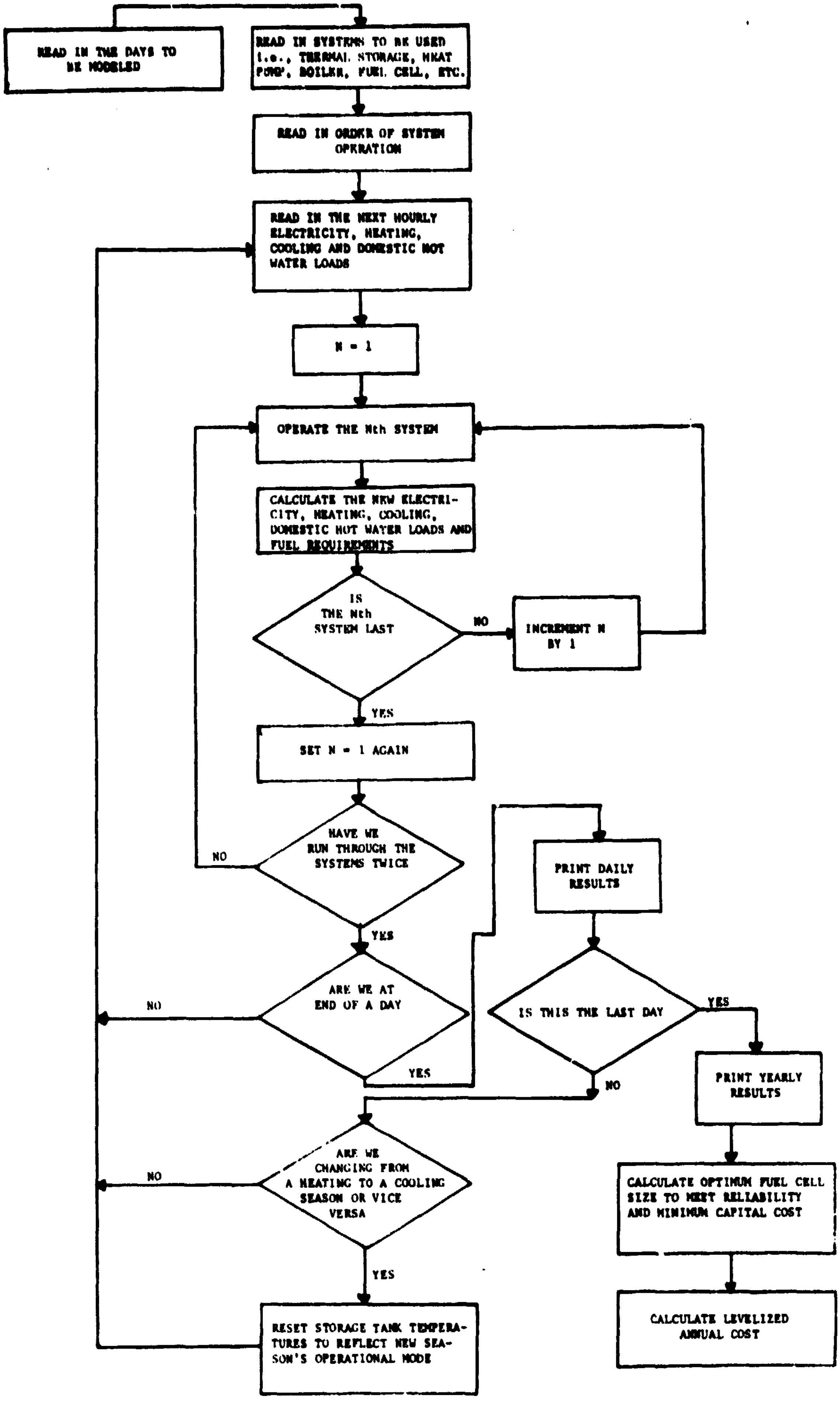
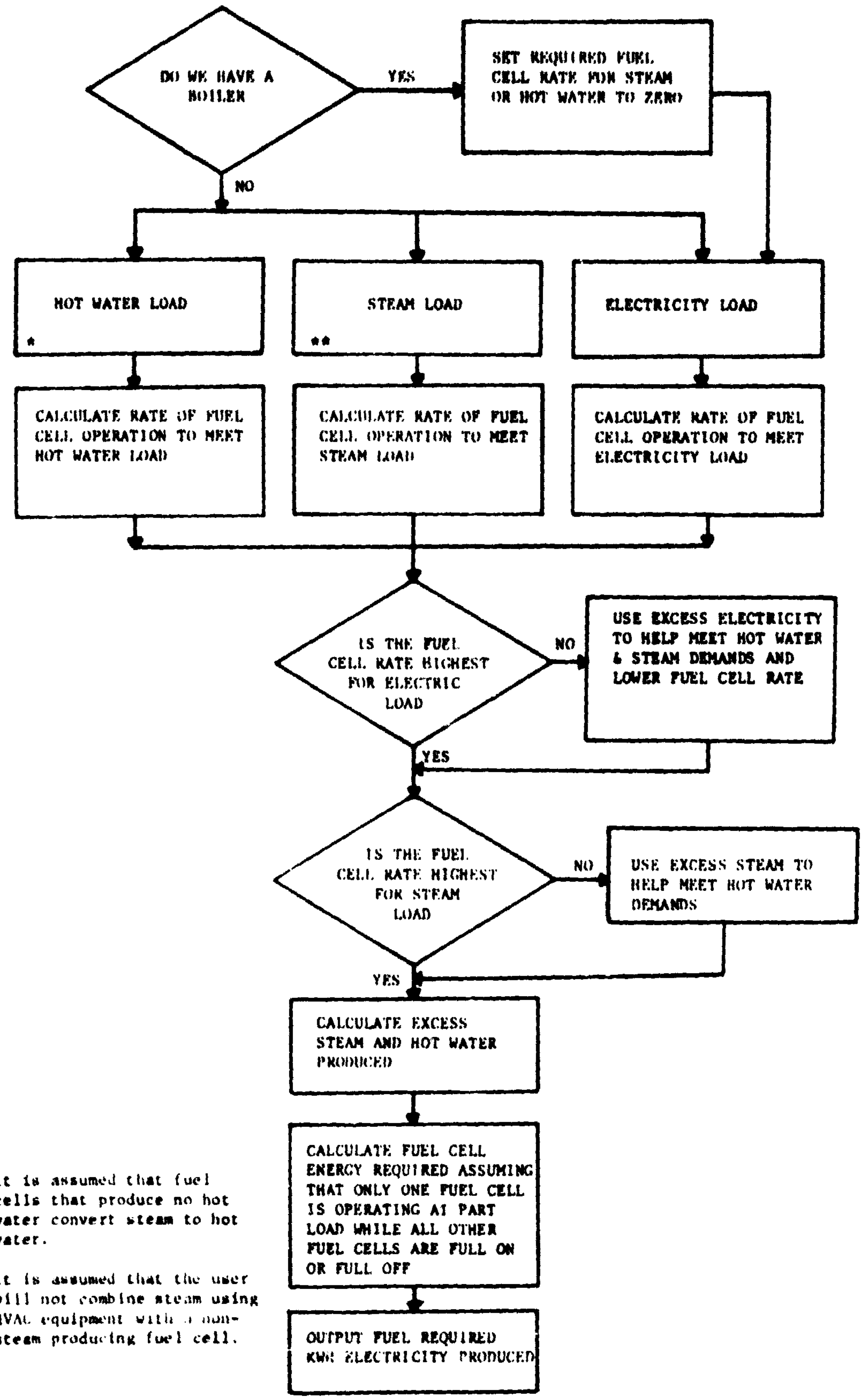


FIGURE 9A

OVERALL FUEL CELL PROGRAM

FIGURE 9B

FUEL CELL SYSTEM



* It is assumed that fuel cells that produce no hot water convert steam to hot water.

** It is assumed that the user will not combine steam using HVAC equipment with a non-steam producing fuel cell.

FIGURE 9C
HOT WATER HEATER SYSTEM

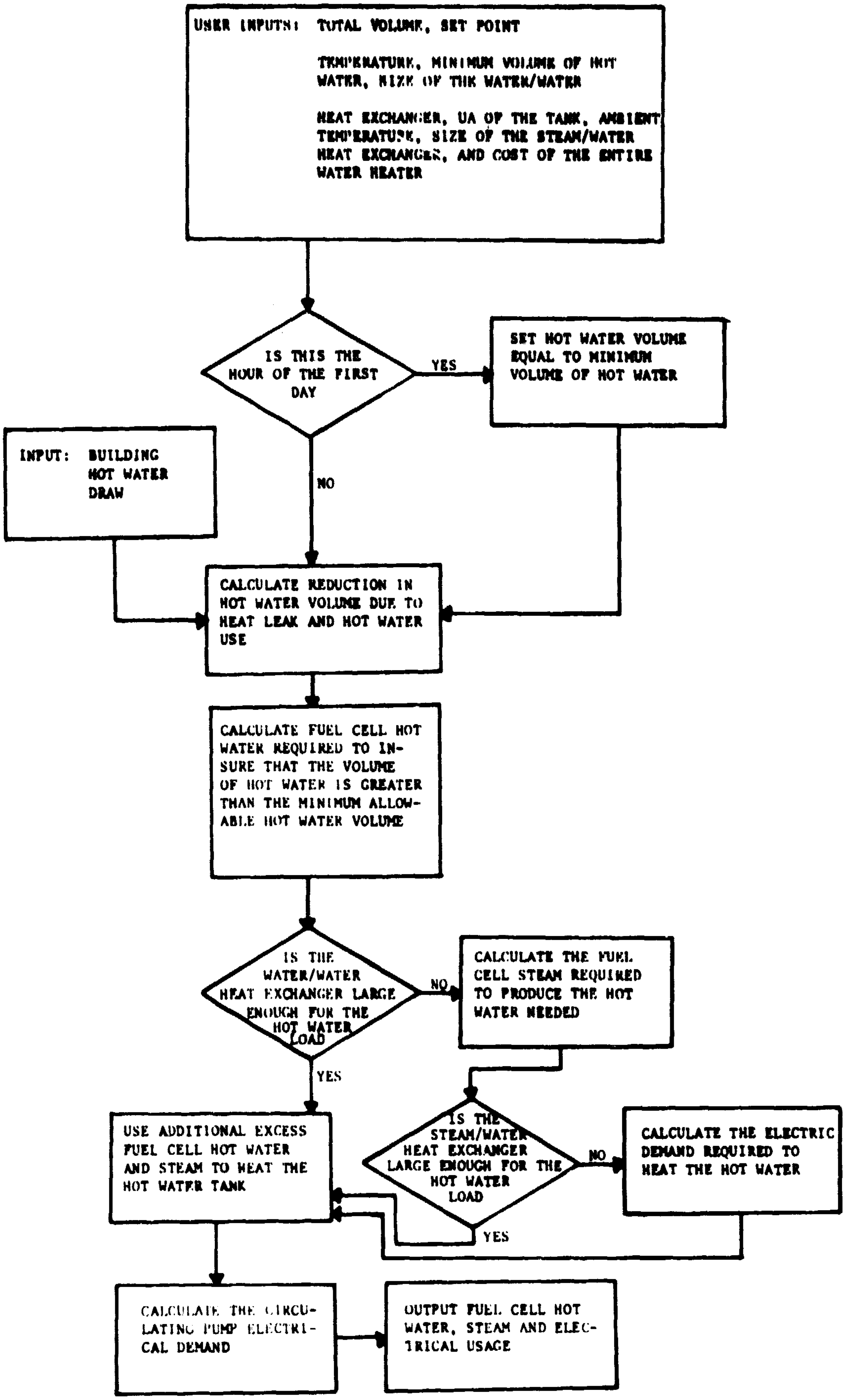
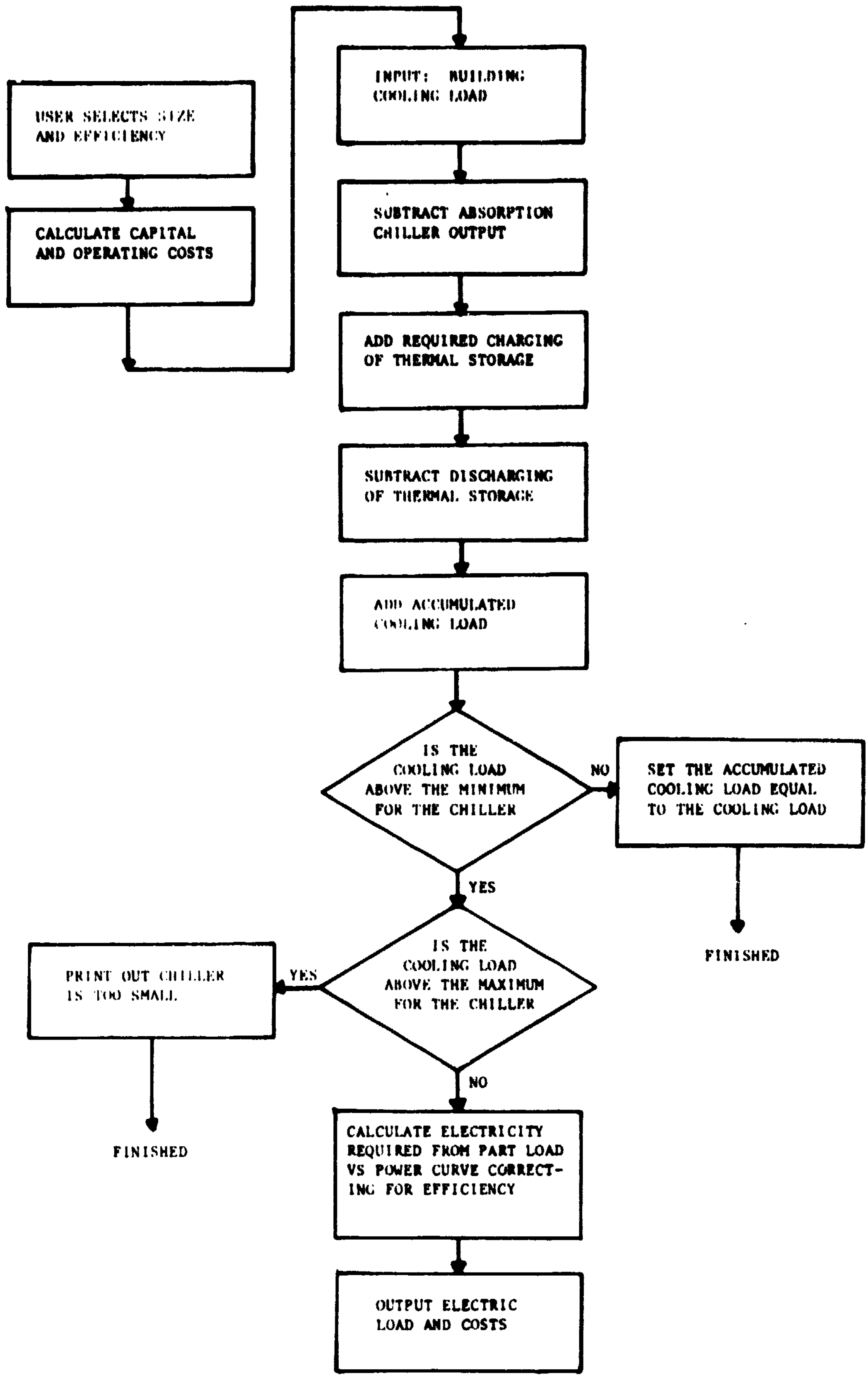


FIGURE 9D

CENTRIFUGAL CHILLER SYSTEM*



* The reciprocating chiller system is similar.

FIGURE 9E
GAS/OIL BOILER SYSTEM

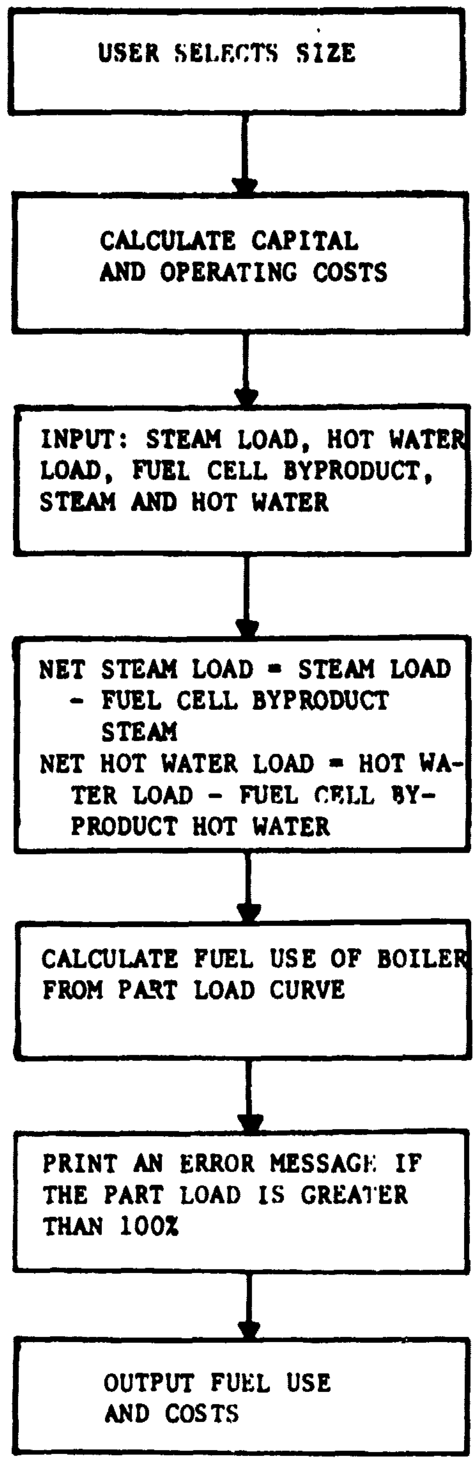


FIGURE 9F
FAN COIL SYSTEM

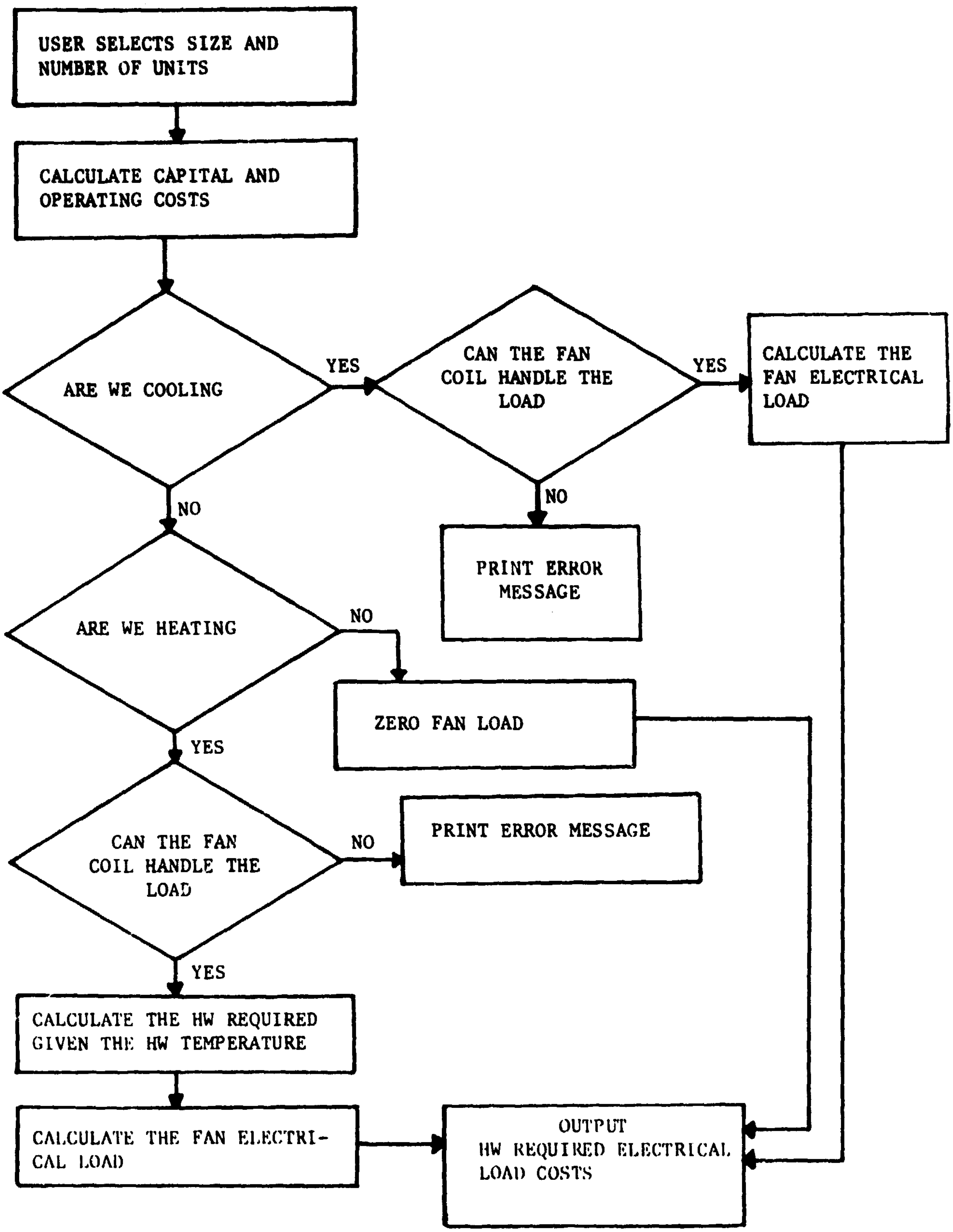


FIGURE 9G

ABSORPTION CHILLER SYSTEM

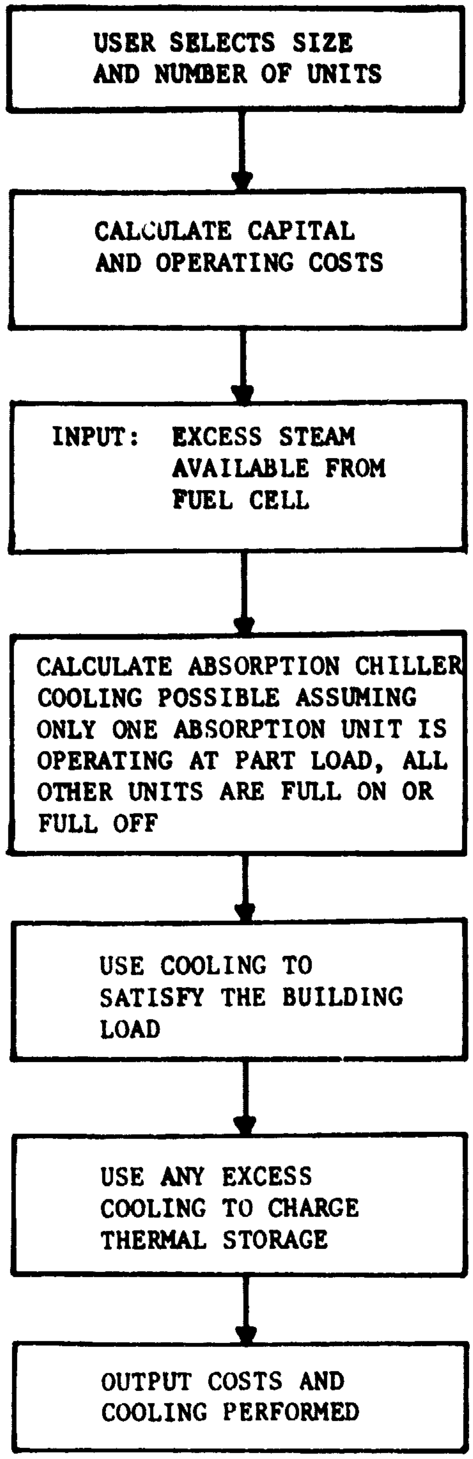
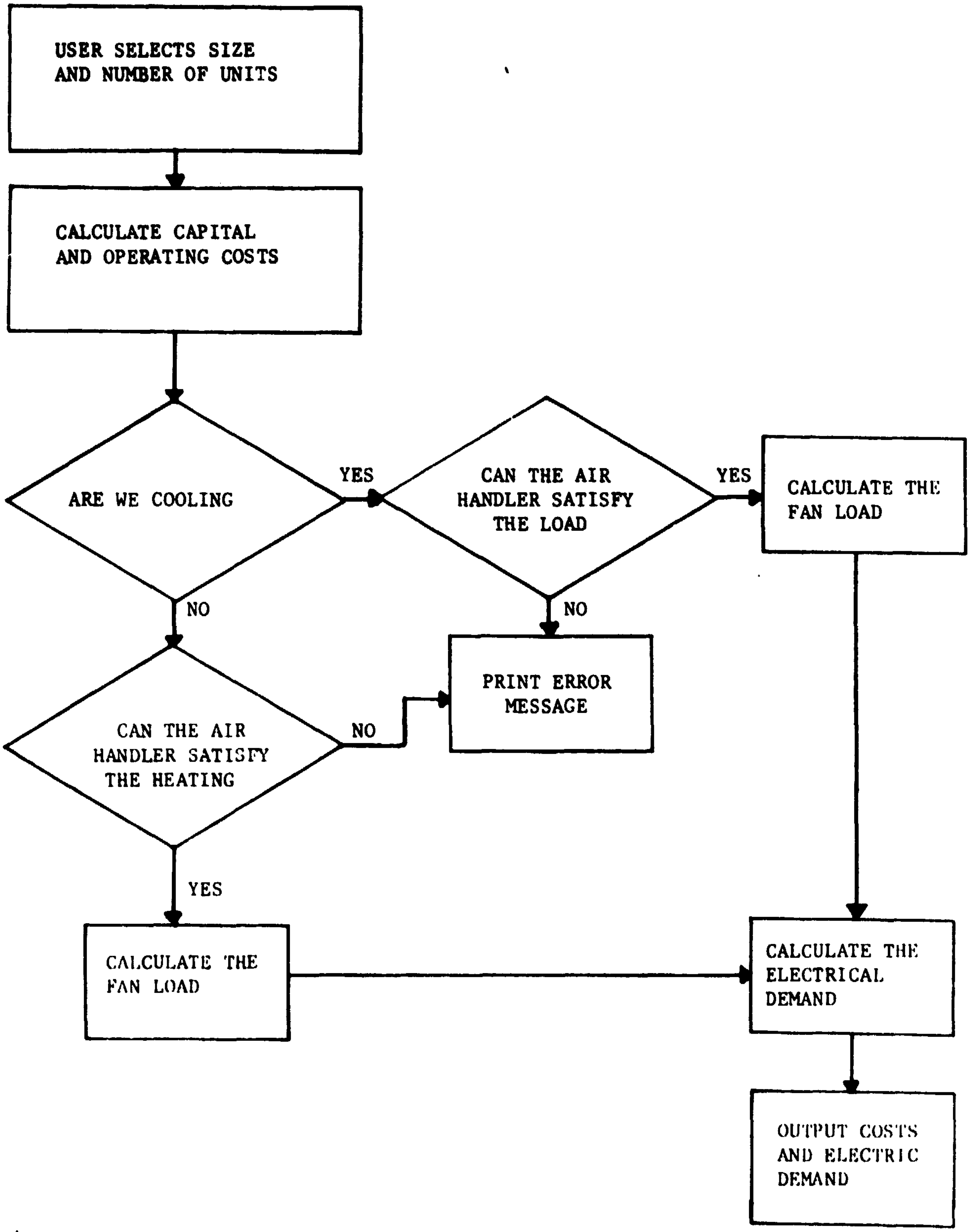


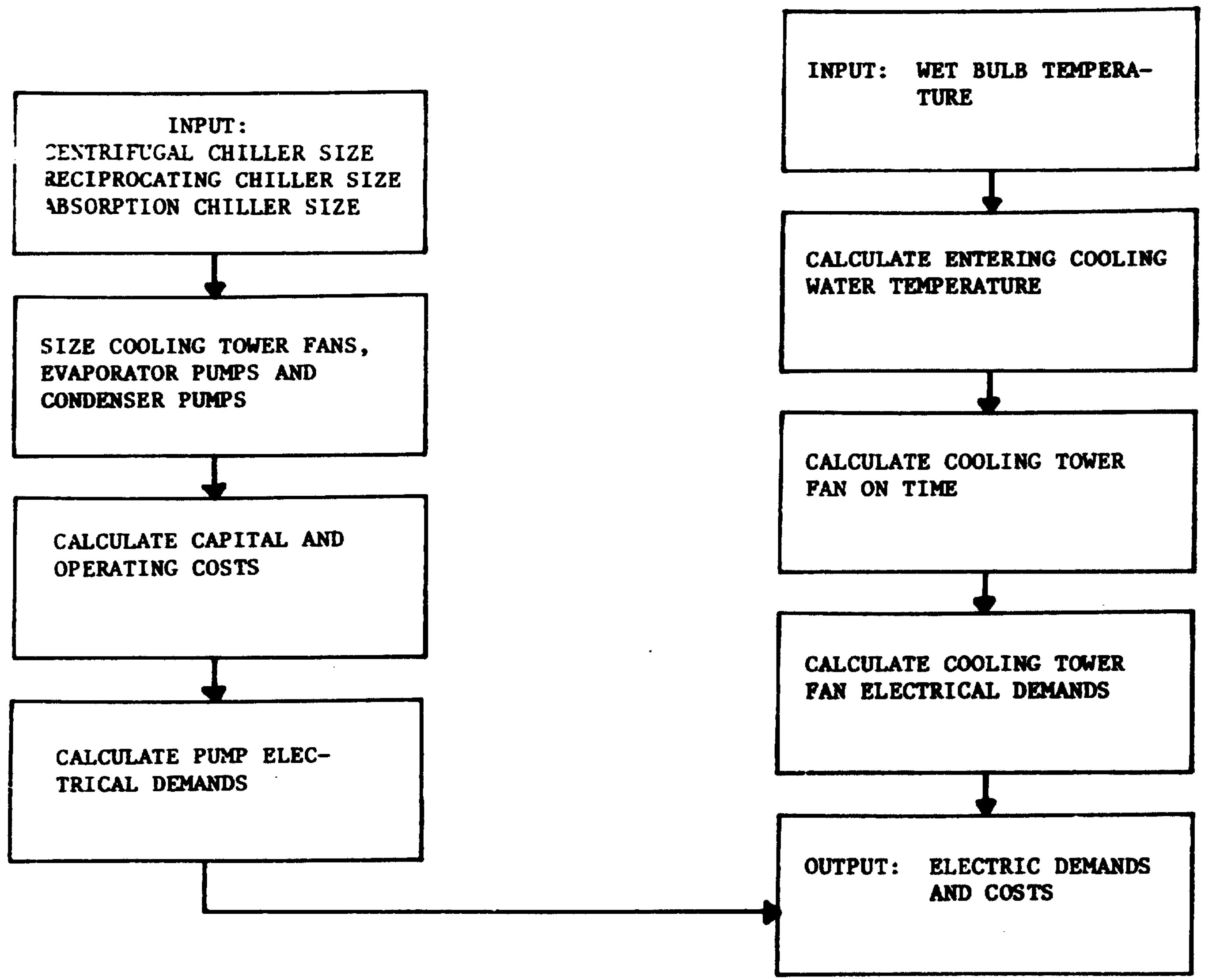
FIGURE 9H

AIR HANDLING* SYSTEM



* The cabinet unit heater system logic is similar.

FIGURE 91
COOLING TOWER SYSTEM



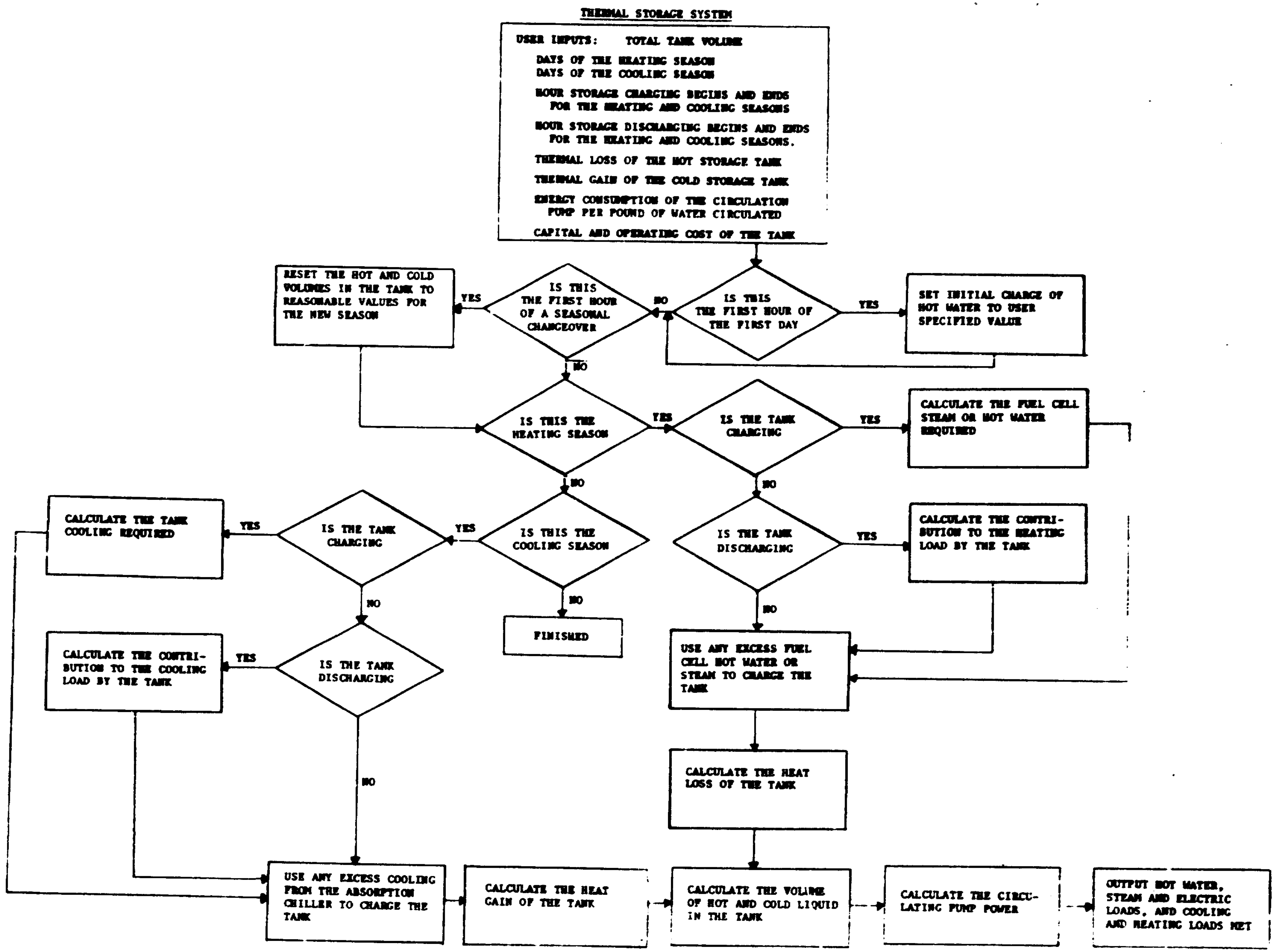

THERMAL STORAGE SYSTEM
USER INPUTS: TOTAL TANK VOLUME
DAYS OF THE HEATING SEASON
DAYS OF THE COOLING SEASON
HOUR STORAGE CHARGING BEGINS AND ENDS FOR THE HEATING AND COOLING SEASONS
HOUR STORAGE DISCHARGING BEGINS AND ENDS FOR THE HEATING AND COOLING SEASONS.
THERMAL LOSS OF THE HOT STORAGE TANK
THERMAL GAIN OF THE COLD STORAGE TANK
ENERGY CONSUMPTION OF THE CIRCULATION PUMP PER POUND OF WATER CIRCULATED
CAPITAL AND OPERATING COST OF THE TANK
IS THIS THE FIRST HOUR OF THE FIRST DAY
YES
SET INITIAL CHARGE OF HOT WATER TO USER SPECIFIED VALUE
NO
IS THIS THE FIRST HOUR OF A SEASONAL CHANGEOVER
YES
RESET THE HOT AND COLD VOLUMES IN THE TANK TO REASONABLE VALUES FOR THE NEW SEASON
NO
IS THIS THE HEATING SEASON
YES
IS THE TANK CHARGING
YES
CALCULATE THE FUEL CELL STEAM OR HOT WATER REQUIRED
NO
IS THE TANK DISCHARGING
YES
CALCULATE THE CONTRI-BUTION TO THE HEATING LOAD BY THE TANK
NO
USE ANY EXCESS FUEL CELL HOT WATER OR STEAM TO CHARGE THE TANK
CALCULATE THE HEAT LOSS OF THE TANK
NO
IS THIS THE COOLING SEASON
NO
FINISHED
YES
IS THE TANK CHARGING
YES
CALCULATE THE TANK COOLING REQUIRED
NO
IS THE TANK DISCHARGING
YES
CALCULATE THE CONTRI-BUTION TO THE COOLING LOAD BY THE TANK
NO
USE ANY EXCESS COOLING FROM THE ABSORPTION CHILLER TO CHARGE THE TANK
CALCULATE THE HEAT GAIN OF THE TANK
CALCULATE THE VOLUME OF HOT AND COLD LIQUID IN THE TANK
CALCULATE THE CIRCU-LATING PUMP POWER
OUTPUT HOT WATER, STEAM AND ELECTRIC LOADS, AND COOLING AND HEATING LOADS MET

FIGURE 9

A large data base of component systems performance and cost data were developed in Task 1 and is summarized in Volume II of this report. These data were integrated into the computer model so that capital costs could be calculated allowing the user to quickly perform component sizing optimization studies to identify the optimal integration scheme. The cost data were developed parametrically based on both component capacity and efficiency. The user selects a component efficiency and the model automatcially costs the major components necessary to meet the load demand.

The size and number of fuel cells needed to meet the reliability requirements are calculated in the model using a standard loss-of-load probability analysis explained in Section 4.4.1. The program selects a reasonable fuel cell size starting with the minimum possible number of fuel cells. The reliability for this configuration is calculated. If the reliability is below the minimum specified, another fuel cell is added and the reliability is recalculated. This process is repeated until the minimum specified reliability is met or exceeded. Once the size and number of fuel cells is known, the fuel cell capital cost can be calculated. Other fuel cell sizes are then selected and the entire process repeated, until the model has determined which fuel cell size leads to a minimum capital cost.

4.2 Economic Measures

The primary economic measure used in this study was Levelized Annual Cost which combines the investment costs and operating costs of the fuel cell total energy system into a single figure for comparison. The levelized annual cost concept was developed for the electric utility industry analysis of central power plants. This cost measure was used exclusively during the system optimization work as the figure of merit.

Cash Flow analysis and a Rate of Return calculation, both more familiar to the building developer was then used to characterize the best systems.

These latter analyses permit different sectors of the business community to evaluate the systems using their own particular financial guidelines most suited to their business. The following paragraphs describe the formulation of these economic measures. All costs are in 1978 dollars.

Levelized Annual Cost

The following formulation was taken principally from: NASA Documents dated April 12, 1979. Groundrules for Economic Analysis

The Levelized Annual Cost (LAC) is a comparative measure of both the fixed and variable costs associated with the investment, incurred at different times throughout the life of the project. The formulation attempts to account for the real cost of money by using a Capital Recovery Factor (CRF_r) applied to determine the present value of energy costs and a fixed charge rate (FCR) similar to a mortgage applied to the capital investment. The levelized annual cost is defined as:

$$LAC = C \cdot FCR + NO + \left[\sum_{n=1}^{N} \frac{E(1+e)^n}{(1+r)^n} \right] CRF_r$$

Where:	LAC	=	levelized annual cost
	C	=	capital investment
	FCR	=	fixed charge rate; function of cost of capital, project life, tax treatment, etc.
	E	=	energy cost
	e	=	escalation, decimal
	r	=	after tax cost of capital
	CRF_r	=	capital recovery factor at r
	NO	=	non-energy operating cost (Levelized)

$$FCR = \frac{CRF_r}{1-t} \quad [1 - t\ (DEP) - TC]$$

Where: CRF is capital recovery factor for the after tax cost or capital r and the economic life N t = tax rate

TC = investment tax credit rate

DEP = levelized depreciation factor for Sum of Years Digits (SYD)

$$DEP = \frac{2\left[NT - \frac{1}{CRF_{r,NT}}\right]}{NT\ (NT+1)_r}$$

(NT = tax life, $CRF_{r,NT}$ is for after tax cost of capital r and tax life NT).

All values used in this study are in constant 1978 dollars and inflation is not addressed although escalation of energy costs is included. For the purpose of comparing the performance of different systems the following constants were used:

r = .10 cost of capital after taxes with no inflation

C = .10 investment tax credit rate

t = .50 income tax rate

Using these values and assuming a project and tax life of 25 years then:

CRF_r = .1102

(for r = .10 and economic life of 25 years)

DEP = .490

(for r = .10 and tax life of 25 years)

and combining these relations and values:

FCR = .1444

<u>Energy Cost and Real Escalation</u>

Source: December, 1978, Mid-Term Energy Forecasting System MEFS - Energy Information Administration (EIA).

(Energy costs in 1978 dollars/million BTU)

	1980	1995	e*
Electricity	\$12.39	\$13.49	.6%
Gas	\$3.03	\$4.33	2.4%

Other Input Assumptions

$$CRF_r = .1102$$

for r = .10 and an economic life of 25 years.

Combining These Relations

$$LAC = .1444\ C + NO + .1102 \sum_{n=1}^{25} \frac{E(1+e)^n}{(1.10)^n}$$

Non-Energy Operating Costs

Sum of maintenance costs, and insurance and local taxes. We have assumed that insurance and local taxes are (.03)C. Maintenance costs are obtained from the component data base and NASA supplied fuel cell data.

Later in this study the following alternative financial analysis methods will be discussed from the viewpoint of the developer (Chapter 5.4). The following format is used in Volume II, Section 4 to present the Cash Flow Analysis:

			Operating Costs	
Year	Incremental Cash Flow	Discounted Cash Flow	Cash Flow Fuel Cell System	Cash Flow Baseline System
0				
1				
2				
3				
4				
.				
.				
.				
.				
25				

* e = average escalation rate compounded annually.

The Rate of Return analysis provides the interest rate at which the present value of the yearly operating cost savings* equals the initial additional capital investment of the fuel cell system compared to a conventional system. The equation used is:

$$\text{Capital Investment} - \sum_{n=1}^{25} \frac{\text{Operating Cost in Years n}}{(1 + i)^n} = 0$$

* Note: For this analysis to be valid the fuel cell must provide every year a net operating cost savings. Also, for clarity, taxes and insurance are not included.

4.3 Conventional System Performance

The four conventional systems were simulated in the integration system model. The four systems are: (1) gas boiler and electric chiller store (2) all electric store (3) gas boiler and electric chiller apartment (4) all electric apartment.

The initial analyses calculated the annual performance using 36 days of weather data on an hour-by-hour calculation. The number of days were reduced parametrically to four particular days: 2 peak days and 2 mean days, resulting in a predicted levelized annual cost performance within 1.8% of using 36 days in the store.* This same approach was taken for a representative fuel cell based system and the agreement was 4.9% between 36 days of simulation and the 4 particular days.

It was possible to obtain a reasonable approximation to a yearly run with only four actual days of data for the following reasons:

1) The peak heating and cooling days were included in the data insuring that the HVAC equipment was properly sized.

* The normal demand of the store is more dependent on outdoor conditions because of the small fraction of domestic water heating. It was chosen as the worst case test.

2) The daily hot water usage profile was essentially constant.

3) The daily non-HVAC electrical use profile was also essentially constant.

4) The daily fuel cell usage was determined primarily by the electrical demand which caused the fuel cell load to be relatively constant.

5) Both the store and to a lesser extent the residential buildings have heating and cooling loads that are primarily affected by internal sources (i.e., lights and people) rather than the weather. Thus, the store's and the residential building's daily heating and cooling profiles tend to be relatively constant from day to day.

The conventional component sizes found necessary to meet the demand are given below:

	Store	Garden Apartment
Boiler (KW Gas Heating)	322	470
Chiller (KW Cooling)	1214	352
Domestic Hot Water (Liters)	1700	6800

The results of the simulation are summarized in Table 3 based on the economic variables in Chapter 4.2. The capital cost of a gas heated building is slightly more than a comparable electric heated building but the annual energy costs are substantially less, resulting in a lower levelized annual cost for a gas based HVAC conventional system.

The format of Table 3 which presents system performance is repeated in Volume II, Section 3.0 for all of the systems analyzed in the study.

TABLE 3

CONVENTIONAL HVAC SYSTEM PERFORMANCE

(All Values Except Capital Cost are Annual Costs)

RETAIL STORE

	Levelized Annual $	Capital* $	Operating & Maintenance $	Total Energy $	Gas $	Electricity $
Gas	188952.12	258204.00	24465.12	119912.06	5312.49	114599.62
Electric	194535.87	243030.00	23620.90	129027.87	0.0	129027.87

GARDEN APARTMENT

	Levelized Annual $	Capital* $	Operating & Maintenance $	Total Energy $	Gas $	Electricity $
Electric	175498.50	174548.00	21493.44	122358.00	0.0	122358.0
Gas	143890.69	192548.00	22563.44	85188.87	20937.42	64251.47

* Piping Costs amounting to about $627,500 for the gas system in the store ($515,000 for electric) and $175,000 for the gas and electric apartment are not included.

4.4 Component Selection for Fuel Cell Systems

The key technical analysis of this study is contained in this section in which a methodical approach to selecting the favorable HVAC components for a stand-alone (no electric utility grid connection) on-site fuel cell systems for selected buildings is presented. Table 4a summarizes the available components examined, briefly describes the basis of selection, and indicates the sections in the report in which the details are given. Table 4b is a Master List of all of the system analyzed in this study. Subsequent sections refer to particular systems by a designation code using the following convention:

System	Fuel Cell Type	Building Type	Special Case
Code Number in Series	A - air cooled, near term	S - Store	o Battery Size
	B - liquid cooled, current	A - Apartment	o Fuel Cell Peak Limitation
	C - liquid cooled, advanced		

4.4.1 Fuel Cell Sizing

Three fuel cells described in Section 3.3 were considered in both the Retail Store and Garden Apartment application. They are:

- Air Cooled - 210°F Hot Water
- Liquid Cooled - 160°F Water, 60 psig Steam
- Advanced Liquid Cooled - 60 psig Steam

The fuel cell sizing was based on a loss of load calculation designed to provide the same reliability as a grid connected electric supply. The standard reliability is 3 hours of outage per 10,000 hours. The following steps were used to calculate the loss of load.

The percent of the time that a certain generating capacity % is exceeded is developed. An example of this data known as a load duration curve is given in Figure 10 (System 4CS). Starting with N=1 a fuel cell size is

TABLE 4

COMPONENT SIZING METHODOLOGY

SECTION	COMPONENT	SELECTION CRITERIA
4.4.1	Fuel Cell	- minimum capital cost to meet stand alone reliability
4.4.2	Gas Boiler	- sized to meet maximum demand
4.4.3	Absorption Chiller	- iterate size to minimize levelized annual cost
	Electric Chiller	- sized to meet maximum demand
4.4.4	Cold Central Thermal Storage	- vary for minimum levelized annual cost
	Pressurized Hot Central Thermal Storage	- not as attractive as cold storage
4.4.5	Domestic Hot Water	- minimum levelized annual cost or minimum size to meet one hour draw, whichever is larger.
4.4.6	Heat Exchanger	- minimum levelized annual cost
4.4.7	Water to Water Heat Pump	- found not to be economical
	Air to Air Heat Pump	- not used in conventional system;
4.4.8	Cooling Tower, Pump	- as needed
4.4.9	Fan Coil Units, Cabinet Units, and Air Handling Units	- as needed

TABLE 4A

FUEL CELL A APARTMENT

RUN	FUEL CELL		BOILER	CHILLER		THERMAL STORAGE			NOTES
	NUMBER	MODULE SIZE KW	KW	ABSORPTION KW	ELECTRIC KW	DISCHARGE DUR. HRS.	LITERS	DOMESTIC HOT WATR. LITERS	
1AA	21	20.8	0	0	351	1	1680	6814	
2AA	21	20.8	0	0	351	2	2404	6814	
3AA	21	20.8	0	0	351	0	0	6814	
4AA	21	20.8	410	0	351	1	1680	6814	
5AA	21	20.8	0	88	351	1	1680	6814	6
6AA	21	20.8	410	0	351	1	1680	6814	2
7AA	14	28.0	586	316	351	1	1680	6814	2
8AA-1000	13	20.2	410	0	351	1	1680	6814	2, 3
8AA-500	18	20.4	410	0	351	1	1680	6814	2, 4
9AA	14	28.1	527	316	351	1	1680	6814	5

1 - Water to Water Heat Exchanger Used Throughout - 8098 Watts/°C
2 - High Efficiency Modulated Boiler
3 - Battery Storage 1000 KWH
4 - Battery Storage 500 KWH
5 - The Absorption Chiller Attempts to Limit the Fuel Cell to 200KW
6 - Water-fired Absorption Unit

TABLE 4B

MASTER SYSTEM LIST

FUEL CELL B - APARTMENT

RUN	FUEL CELL		BOILER	CHILLER		THERMAL STORAGE			NOTES
	NUMBER	MODULE SIZE KW	KW	ABSORP-TION KW	ELECTRIC KW	DIS-CHARGE DUR.HRS.	LITERS	DOMESTIC HOT WATR. LITERS	
1BA	14	31.1	0	1-88	351	1	1,680	6814	1,2,3
2BA	14	31.1	0	1-88	351	2	2,404	6814	1,2,3
3BA	15	28.7	0	1-88	351	4	10,390	6814	1,2,3
4BA	17	25.5	0	1-88	351	8	36,560	6814	1,2,3
5BA	18	25.9	0	1-88	351	12	63,080	6814	1,2,3
6BA	18	24.4	0	0	351	0	0	6814	1,2,3
7BA	14	31.1	0	1-88	351	0	0	6814	1,2,3
8BA	18	24.4	0	0	351	1	1,680	6814	1,2,3
9BA	21	20.5	0	0	351	1	1,680	6814	1,3
10BA	21	20.5	322	0	351	1	1,680	6814	1,3
11BA	21	20.8	0	175	316	1	1,680	6814	1,3
12BA	21	20.5	0	0	351	1	1,680	13630	1,12
13BA	21	20.5	322	0	351	1	1,680	6814	1,3,9
14BA-8000	17	22.8	0	0	351	1	1,680	6814	1,3,4
14BA-4000	20	20.0	0	0	351	1	1,680	6814	1,3,5
14BA-2000	21	20.6	0	0	351	1	1,680	6814	1,3,6
14BA-1000	16	21.3	0	0	351	1	1,680	6814	1,3,7
14BA-500	18	20.4	0	0	351	1	1,680	6814	1,3,8
15BA	14	28.0	527	351	351	1	1,680	6814	1,3
16BA-1000	13	20.0	322	0	351	1	1,680	6814	1,3,10
16BA-500	18	20.4	322	0	351	1	1,680	6814	1,3,11

1 - A 7832 Watts/°C steam to water heat exchanger
2 - A 8097 Watts/°C water to water heat exchanger
3 - A 8182 liter hot water storage tank
4 - 8000 KWH battery limiting the load to 250 KW
5 - 4000 KWH battery limiting the load to 150KW
6 - 2000 KWH battery limiting the load to 150KW
7 - 1000 KWH battery limiting the load to 200KW
8 - 500 KWH battery limiting the load to 200 KW
9 - High efficiency modulating boiler trying to limit the load to 200KW
10 - 1000 KWH battery limiting the load to 200 KW
11 - 500 KWH battery limiting the load to 200 KW
12 - A 16365 liter hot water storage tank

TABLE 4C

FUEL CELL C - APARTMENT

RUN	FUEL CELL		BOILER	CHILLER		THERMAL STORAGE			NOTES
	NUMBER	MODULE SIZE KW	KW	ABSORPTION KW	ELECTRIC KW	DISCHARGE DUR.HRS.	LITERS	DOMESTIC HOT WATR. LITERS	
1CA	5	128.0	0	1-88	351	2	2,404	6814	1
2CA	5	128.0	0	1-88	351	4	10,390	6814	1
3CA	5	128.0	0	1-88	351	1	1,680	6814	1
4CA	5	128.0	0	1-88	351	0	0	6814	1
5CA	5	130.0	0	0	351	1	1,680	6814	1
6CA	5	130.0	322	0	351	1	1,680	6814	1
7CA	5	118.1	0	1-176	228	1	1,680	6814	1
8CA	5	130.1	322	0	351	1	1.680	6814	1, 2
9CA	5	110.8	439	316	264	1	1,680	6814	1, 2

1 - A steam to water heat exchanger 7832 watt/°C is used.

2 - High efficiency modulating boiler.

TABLE 4D

RETAIL STORE

RUN	FUEL CELL		BOILER	CHILLER		THERMAL STORAGE			NOTES
	NUMBER	MODULE SIZE KW	KW	ABSORPTION KW	ELECTRIC KW	DISCHARGE DUR. HRS.	LITERS	DOMESTIC HOT WATR. LITERS	
1AS	15	61.48	0	0	984	8	143,800	1700	1
2AS	15	56.71	0	0	984	13	450,460	1700	1
3AS	15	56.95	0	0	773	13	450,460	1700	
4AS	15	60.93	0	0	984	4	74,550	1700	
5AS	15	44.97	1582	1002	0	4	74,550	1700	
6AS	15	65.5	0	0	1125	2	18,313	1700	
7AS	11	85.8	0	1-88	932	4	74,550	1700	
8AS	11	65.0	1582	1002	0	4	74,550	1700	
9AS	10	88.5	644	422	844	4	74,550	1700	
1CS	15	65.5	0	2-88	984	13	450,460	1700	2
2CS	10	107.6	0	2-88	808	8	143,770	1700	2
3CS	7	139.6	0	2-88	633	13	450,460	1700	3
4CS	7	143.5	0	2-88	633	13	378,540	1135	3
4CS-36	9	110.9	0	2-88	633	13	378,540	1135	3,4
5CS	6	144.2	864	844	0	13	378,540	1135	3
6CS	7	136.0	0	2-175	492	13	378,540	1135	3
7CS	7	143.0	0	1-175	633	13	378,540	1135	3
8CS	6	144.0	864	844	0	13	378,540	1135	3
9CS	6	147.0	849	844	492	13	378.540	1135	3

1 - H_2O to H_2O heat exchanger only 2024/watts/°C for all Fuel Cell C cases.

2 - Steam H_2O heat exchanger 1957 watts/°C and 3163 watts/°C H_2O to H_2O.

3 - 1957 watts/°C steam to H_2O heat exchanger only.

4 - This run represented 36 days of data. Otherwise it is exactly the same as 4CS.

TABLE 4E

RETAIL STORE ANALYSIS

**(8-125,000 Cabinet Unit Heaters
4 Air Handling Units)**

RUN	FUEL CELL		BOILER	CHILLER		THERMAL STORAGE			NOTES
	NUMBER	MODULE SIZE KW	KW	ABSORP-TION KW	ELECTRIC KW	DIS-CHARGE DUR.HRS.	LITERS	DOMESTIC HOT WATR. LITERS	
1S	None								
2S									
1BS	15	62.1	0	2-88	984	1	866	1700	
2BS	15	60	0	2-88	984	2	18,314	1700	
3ABS	15	57.6	0	2-88	805	8	143,770	1700	
3BS	15	57.6	0	2-88	984	4	74,550	1700	
4BS	15	57.8	0	2-88	984	8	143,770	1700	
5BS	15	54.0	0	2-88	984	13	453,890	1700	
6BS	15	53.85	0	2-88	633	13	453,890	1700	
7BS	15	58.0	0	2-88	823	4	74,550	1700	
8BS	15	56.8	0	1-88	738	13	378,540	1700	
9BS	15	55.3	0	2-88	633	13	378,540	1700	
10BS	15	58.2	0	0	826	13	378,540	1700	
11BS	15	56.8	0	1-88	738	13	378,540	2271	
12BS	15	56.8	0	1-88	738	13	378,540	1135	
13BS	15	56.7	0	1-88	738	13	378,540	1135	1
14BS	15	55.2	0	2-88	633	13	378,540	1135	1,2
15BS	15	55.3	0	2-88	633	13	378,540	1135	1,3
16BS	15	45.4	1671	1231	0	0	0	1135	1
17BS	11	64.2	1172	844	0	13	378,540	1135	1
18BS	10	80	0	2-88	633	13	378,540	1135	1,4
20BS	15	44.4	1172	844	0	13	378,540	1135	1,5
21BS	15	57.0	0	1-88	879	15	378,540	1135	5
22BS	11	64.2	1172	844	0	13	378,540	1135	6

1 - Eliminate 509 Watts/°C H_2O to H_2O Heat Exchanger, Use Steam to H_2O Heat Exchanger 1957 Watts/°C Only.
2 - High Efficiency (Custom) Absorption Chiller 12# Steam Ton-HR
3 - Relax Fuel Cell Reliability to 30 Hours per 10,000
4 - Relax Fuel Cell Reliability to 10 Hours per 10,000
5 - High Efficiency Absorption Chiller 10# Steam/Ton-HR
6 - High Efficiency Modulating Boiler

TABLE 4F

RETAIL STORE ANALYSIS
(Continued)

RUN	FUEL CELL		BOILER	CHILLER		THERMAL STORAGE			NOTES
	NUMBER	MODULE SIZE KW	KW	ABSORP-TION KW	ELECTRIC KW	DIS-CHARGE DUR.HRS.	LITERS	DOMESTIC HOT WATR. LITERS	
23BS-350	11	65.9	1347	844	510	13	378,540	1135	7
23BS-400	11	65.9	1347	844	510	13	378,540	1135	8
23BS-500	11	74.1	1347	844	510	13	378,540	1135	9
23BS-600	11	76.5	1347	844	510	13	378,540	1135	10
23BS-700	11	78.6	586	334	703	13	378,540	1135	11
25BS	11	64.2	879	844	0	13	378,540	1135	14, 16
26BS	11	64.2	351	844	0	13	378,540	1135	15, 17
27BS	13	35.1	1172	844	0	13	378,540	1135	12
28BS	15	55.3	0	2-88	633	13	378,540	1135	14
29BS	15	55.3	0	2-88	633	13	378,540	1135	15
30BS	15	59.2	0	2-88	633	13	378,540	1135	13

7 - 350KW Peak Limiting by Absorption Unit
8 - 400KW Peak Limiting by Absorption Unit
9 - 500KW Peak Limiting by Absorption Unit
10 - 600KW Peak Limiting by Absorption Unit
11 - 700KW Peak Limiting by Absorption Unit
12 - 3000KWH Battery Trying to Hold the Load at 350KW
13 - Adiabatic Thermal Storage Tank
14 - High Efficiency Absorption Chiller 12# Steam/Ton-Hour
15 - Higher Efficiency Absorption Chiller 6# Steam/Ton-Hour
16 - 880KW Boiler
17 - 350KW Boiler

selected equal to the maximum generating capacity required divided by N and the loss of load probability is calculated using the standard relation:

$$R = \sum_{i=0}^{m} \overbrace{[a^{m-i}\,(1-a)^{i}]\ [\frac{m!}{(m-i)!\ i!}]}^{\text{Likelihood of Delivery}}\ (\text{plec}) \qquad i = \#\ \text{of fuel cells that have failed.}$$

Where:

a = fuel cell reliability

plec = the probability that the load exceeded the capacity of (m-i) x (fuel cell size)

m = no. of fuel cells. m is increased until the overall reliability desired is met or exceeded.

From this calculation the size and number of fuel cells are identified and the total fuel cell cost is calculated based on data in Table 2. The process is repeated with N incremented by 1 until the minimum fuel cell cost is found. A typical output of these data is given in Table 5. The lowest cost fuel cell in this example is the 143.47KW size.

The fuel cell reliability criterion has the effect of specifying standby fuel cells. Table 6 summarizes the reliability requirement for the different fuel cell types. Relaxing the reliability criterion will reduce the system cost and the levelized annual cost as shown in Table 7. Due to the reliatively flat cost/capacity relations in the reliability calculation, a relatively wide range of capacities ($\pm$ 20KW) can meet the reliability criteria at about the same capital cost. This accounts for the dispersion of optimum sizes shown in Table 5. These data should not be construed as showing a real difference in optimum modules size as a function of reliability, but rather a reduction in total installed power with relaxed reliability.

FIGURE 10

TYPICAL LOAD DURATION CURVE

(Case 4CS)

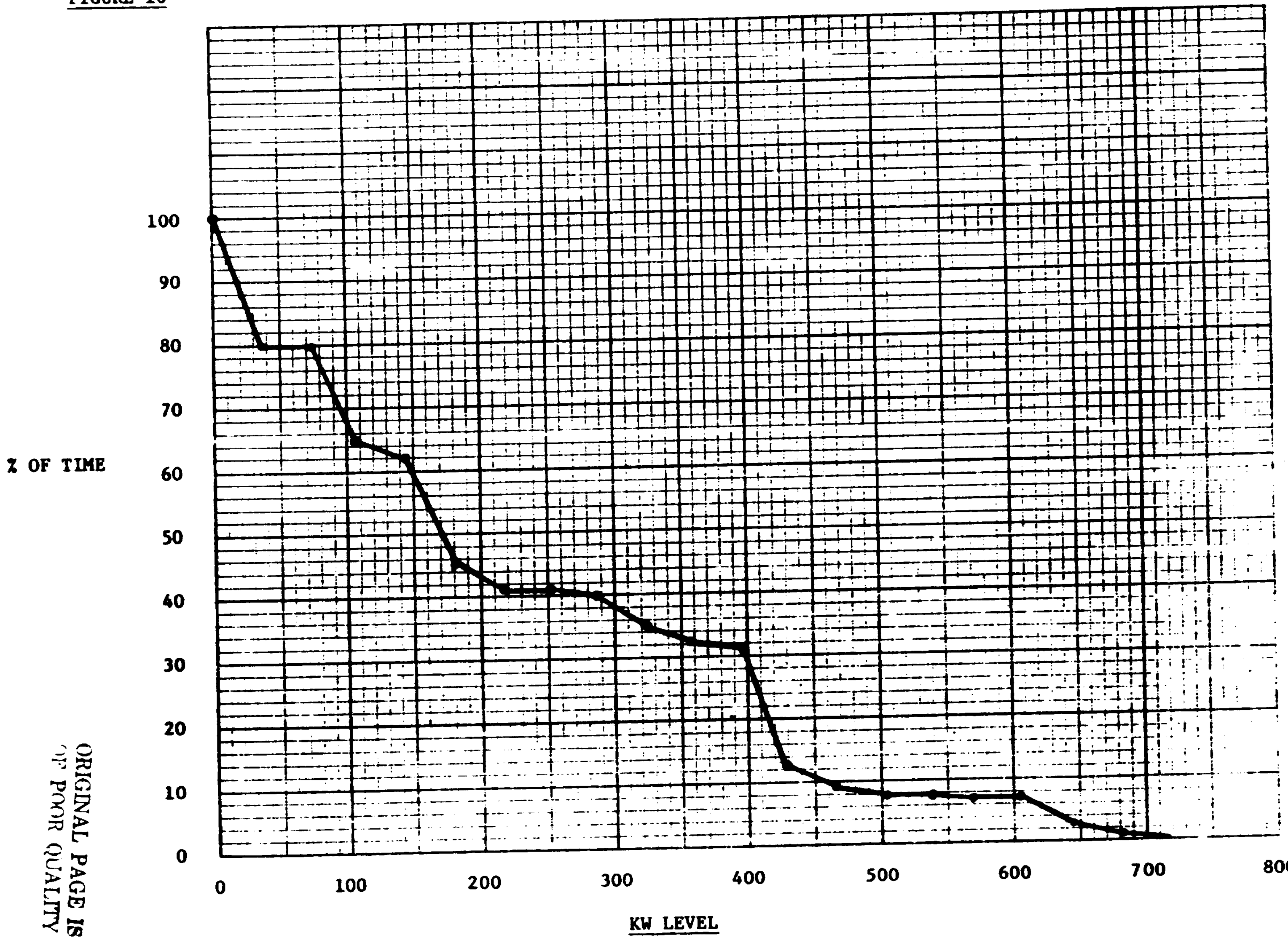


TABLE 5

FUEL CELL SIZE SELECTION

(case 4CS)

Cost $	Fuel Cell Size (KW)	Number of Fuel Cells	Total Installed Capacity (KW)
511,785	358.67	4	1434.7
437,045	239.11	5	1195.6
400,247	179.33	6	1076.0
378,655	143.47	7	1004.3
410,221	119.56	9	1076.0
394,369	102.48	10	1024.8
385,414	100.00	10	1000.0

TABLE 6

PERCENTAGE STANDBY FUEL CELL CAPACITY DUE TO RELIABILITY CRITERIA OF 3 HOURS OUTAGE PER 10,000

BLDG / FUEL CELL	APARTMENTS	STORE
A, C	10 - 20%	15 - 25%
B	60 - 70%	40 - 50%

TABLE 7

EFFECT OF RELIABILITY ON COST

(FUEL CELL B - STORE)

RUN	INSTALLED KW	RELIABILITY OUTAGE/1000 HOURS	LEVELIZED ANNUAL COST IN $1,000
13BS	15@56.7 KW = 850 KW	3	249.0
18BS	10@79.8 = 798 KW	10	245.7
15BS	16@47. = 752 KW	30	245.4

It should be noted that the fuel cell operating and maintenance cost is based on 6 mils per KWH of delivered energy. As a consequence of this, the O&M cost for the fuel cell is relatively independent of the installed fuel cell capacity and is a function of the load. Therefore, a reduction in fuel cell capacity as a result of thermal storage, relaxation of reliability, battery storage and fuel cell type will not reduce operating and maintenance costs. O&M costs exert a substantial effect on system economics since they are about equal to the total fuel cost.

4.4.2 Gas Boiler

The gas boiler is used as an auxiliary source of steam and can be used to meet both the heating functions (hot water and space heating) as well as the cooling function when used in connection with an absorption chiller. Judicious use of a boiler may reduce the installed fuel cell capacity required.

In the systems analysis it was found that when the auxiliary boiler is used to meet only the domestic hot water and space heating functions, the fuel cell size is not affected. The peak demand, which sets the fuel cell size is the summer air conditioning load in both the Garden Apartment and the Retail Store. System 4AA of Table 8 shows that the fuel cell size is not changed when the auxiliary boiler is used to supplement space and water heating.

To reduce the fuel cell size the boiler must be used in conjunction with a larger absorption chiller. The analysis shows that the boiler offers no net cost savings because the capital cost savings of the reduced fuel cell installation is more than offset by the added fuel cost and chiller cost. Table 8 shows the results of the use of an auxiliary boiler on the system economics of the apartment and Table 9 which clearly shows the effect of an auxiliary boiler on the fuel cell cost with and without absorption chillers and the net effect on the annual cost.

TABLE 8

EFFECT OF AUXILIARY BOILER ON SYSTEM ECONOMICS - GARDEN APARTMENT

Reference Run	Without Boiler 3AA	Boiler-Heating 4AA	Boiler-Absorption Chiller 9AA
Fuel Cell	$170,506	$170,506	$150,025
Boiler	0	$ 9,528	$ 11,927
Absorption Chiller	0	0	$ 34,650
Total Capital Cost Including Cooling Tower and Distribution Equipment	$355,400	$365,400	$389,178
Annual Fuel Cost	$48,946	$49,449	$ 51,442
Levelized Annual Cost	$149,136	$159,909	$160,068
Absorption Chiller Size (KW)	0	0	316
Electric Chiller Size (KW)	351	351	351

TABLE 9

EFFECT OF AUXILIARY BOILER ON SYSTEM ECONOMICS

	Without Boiler Run 13BS	With Boiler Run 16BS
Capital Cost	$732,000	$676,000
Annual Fuel Cost	$ 73,000	$ 98,000
Levelized Annual Cost in 1000	$249,000	$270,000
Absorption Chiller Size (KW)	88	1231
Electric Chiller Size (KW)	739	0

4.4.3 Chillers (Electric and Absorption)

In general, the chillers are sized to just meet the peak cooling load. The partitioning between absorption and electric chillers is based on an iterative process aimed at minimizing levelized annual cost. The optimum cooling load split for the store was 10% absorption chiller and 90% electric chiller because the absorption unit requires about 5 times as much energy as the electric unit and costs about 40% more per ton.

The least annualized cost systems for the garden apartment have no absorption chillers. The hot water and steam could more effectively be used to meet the steady domestic hot water demand. In addition, the non-steady relatively low cooling load (as compared to the store) was best met with electric chillers.

A system with 100% absorption chiller and no electric was designed with the purpose of using all of the fuel cell steam output and reducing the fuel cell installed capacity due to the reduced electric load. As discussed in Section 4.4.2., using 100% absorption chiller may reduce the fuel cell installation cost but will cause a net levelized annual cost increase due to a $23,000 per year fuel cost increase as shown in Table 10.

An alternative to the two approaches above is to have nearly 100% absorption and 100% electric chiller capacity (run 7AA) and to use the absorption chiller during high base electric demands and the electric chiller during the other periods in order to flatten the fuel cell electric load and improve the thermal performance. The total capital cost increase, however, offsets the substantial ($42,000) fuel cost savings.

Large amounts of 210°F hot water are available from the Fuel Cell B and 25 ton absorption units are available that can operate at this temperature. These chillers cost $360 per KW* (1264/ton) and have a COP of 1200 lbs HW/ton of cooling. The system LAC with such a unit is 155,000 compared to the baseline value of 149,000.

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* Operated with steam at 240°F the cost is $252 per KW, using 210°F water the actual capacity drops to 70% of rated.

TABLE 10

PARTITIONING OF ABSORPTION AND ELECTRIC CHILLERS

(All Costs in $1,000)

	Retail Store			
Absorption Chiller Capacity as a % of Peak Load	0	10	100	100%
Electric Chiller Capacity as a % of Peak Load	100%	90	0	100
System Number	10BS	13BS	17BS	23BS
Fuel Cell	447	437	347	435
Total Capital	726	732	671	763
Annual Fuel Cost	74	73	96	32
LAC	249.2	249.0	265.0	268.3

4.4.4 Central Storage (Hot and Cold)

Besides the domestic hot water storage (potable water) a larger central facility was employed in much of the analysis. In the winter this unit stores boiler water for space heating peak load shaving. In the summer the same unit is used to reduce the peak cooling rate through chilled water storage. A hot storage (steam) ahead of the absorption chiller was considered and found to be economically unfeasible as discussed below.

Steam storage input to the absorption unit may reduce the peak demand on the fuel cell size but will not reduce the peak on the chillers which must be sized to meet the maximum cooling load. A decrease from a 288 KW absorption unit plus 984KW electric chiller (System 1BS) to 1-88 KW absorption and 735KW electric (System 13BS) is experienced when 378,540 liters of cool storage is used. This is a savings of $36,100* of installed chiller. The total capital cost of cool storage is about $45,800 for an above ground tank (insulated to 0.5-7 watt/M^2 - °C (0.1 BTU/HR-Ft^2 - °F).

Assuming a COP (coefficient of performance) of about .67 for the absorption unit, a steam storage capable of handling about 561 kilogramms** (1238 lbs) of steam would be required. This amounts to a 484,507 liter 184 KPA (12 psig) storage which is larger, pressurized and therefore, considerably more expensive than the cool water storage.

Cool storage reduces chiller installed cost and requires less volume than a comparable hot storage facility which does not offer the benefit of reduced chiller capacity. Cool storage is clearly more favorable than hot storage.

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* About $782 per absorption chiller and $13,980 savings (200 per ton) for centrifugal electric chillers.

** 378,500 liters at 5.5°C cooling water rise is equivalent to about 561 (1238 lbs) kilograms of 183 KPA (12 psig) steam which is available from the fuel cell.

TABLE 11

CENTRAL THERMAL STORAGE EFFECT ON COST

(All Cases With Fuel Cell B)

	Reference Run Number	Liters of Storage*	Levelized Annual Cost (LAC)	Comments
	7BA	0	166.9	
	1BA	1,681	166.7	Min.LAC
GARDEN	2BA	2,400	167.1	
APARTMENT	3BA	10,390	167.3	
	4BA	36,560	169.8	
	5BA	63,080	175.4	
	1BS	886	258.5	
RETAIL	2BS	18,314	255.5	
STORE	4BS	143,770	256.2	
	13BS	378,540	249.0	Min.LAC
	6BS	453,890	250.9	

* An above ground tank insulated to 0.567 watt/M^2-°C (0.1 BTU/HR - FT^2-°F) was used.

The selection of central storage tank size cannot be done apriori. The chiller and fuel cell sizes will be affected by the cool storage capacity. A series of computer runs were made with a variety of cool storage tank sizes and a minimum of levelized annual cost was sought, the results are given in Table 11 for Fuel Cell B. Cool storage for the retail store determines the tank size while the warm water for space heating establishes the tank size in the garden apartment.

Similar analyses were performed with Fuel Cell A and C leading to the following storage volumes:

TABLE 12
SUMMARY OF OPTIMAL CENTRAL STORAGE
(Volumes in Liters)

Building	Fuel Cell B	Fuel Cell C	Fuel Cell A
Retail Store	378,540	378,540	74,550
Garden Apartment	1,681	1,681	1,681

Less storage is indicated for the apartment because it exhibits a flatter load profile and benefits less from storage.

4.4.5 Domestic Hot Water

A separate hot water themal storage for potable domestic water was used. A heat exchanger was employed between the tank and the fuel cell or boiler supply. The demand for domestic hot water in the store was minimal. Several runs (11BS, 8BS, 13BS, Volume 2, Section 3.2) with decreasing storage size were run indicating that the smallest possible tank was the optimal. A tank of the 1135 liters equal to approximately the maximum two hour draw was considered to the minimal size. Using the same reasoning, a 6800 liter tank was used in the garden apartment.

In summary, the large hot water and/or steam supply of the fuel cell can meet all of the domestic water demand without any substantial storage. A minimal size domestic hot water tank equal to approximately the maximum 2 hour demand is used.

4.4.6 Heat Exchangers

Steam and/or hot water from the fuel cell can be used with a heat exchanger to supply potable domestic hot water. Fuel Cell B and A supply hot water and Fuel Cells B and C supply steam so that both water-to-water and steam-to-water heat exchangers were considered.

Fuel Cell B can provide both hot water and steam but it was found that a slightly lower levelized annual cost was achieved when the water-to-water heat exchanger was eliminated and only the steam-to-water unit was used to make hot water.

TABLE 13

EFFECT OF ELIMINATION OF HOT WATER RECOVERY FOR DOMESTIC HOT WATER ON LAC

FUEL CELL B

Reference Run		Retail Store	Garden Apartment
12BS, 8BA	Steam and Hot Water Recovery	$249,136	$162,533
13BS, 9BA	Steam Only	$249,026	$162,094

The final selection of heat exchangers for all of the fuel cells in both buildings is shown in Table 14.

The stand-alone heat exchangers (outside of the heat exchangers in the chiller, boilers and cooling tower) are necessary to develop domestic (potable) hot water. The cost of these heat exchangers range from $1500-$2400 in a system with a total capital cost of $350,000 to $380,000. The effect of heat exchanger selection on the system cost is negligible (.6%).

TABLE 14

HEAT EXCHANGER SIZE

KW/°C (BTU/HR°F)

Building	Fuel Cell B Steam to Water	Fuel Cell C Steam to Water	Fuel Cell A Water to Water
Retail Store	1.96 (3,714)	1.96 (3,714)	2.0 (3,840)
Garden Apartment	7.8 (14,856)	7.8 (14,856)	8.1 (15,360)

4.4.7 Heat Pumps

A water-to-water heat pump could be employed to boost the temperature of the waste heat from the fuel cell. The major benefit of a boost heat pump would probably come in raising hot water to stream for the absorption heat pump rather than discarding the water during the cooling season. The net effect of such a system would be to increase energy consumption, rather than to reduce it. Figure 11 shows that a boost heat pump would require about 3.4 times as much electricity as a standard chiller.

Air-to-air or air-to-water heat pumps will lower the annual energy cost for both the conventional and the fuel cell supported systems. Since heat pumps are not used in the conventional system, they were not employed in the fuel cell systems. Further discussion of the potential benefits of heat pumps is given in 5.26.

4.4.8 Cooling Towers

Cooling towers are an important element in the total system. Cooling tower fan power can amount to $112 to $413 of electricity per year in a typical application (System 2A and 2S) and will vary with the size of the chiller and percent of part load. The cooling tower size is estimated automatically to meet the maximum output of the chiller.

4.4.9 Auxiliaries

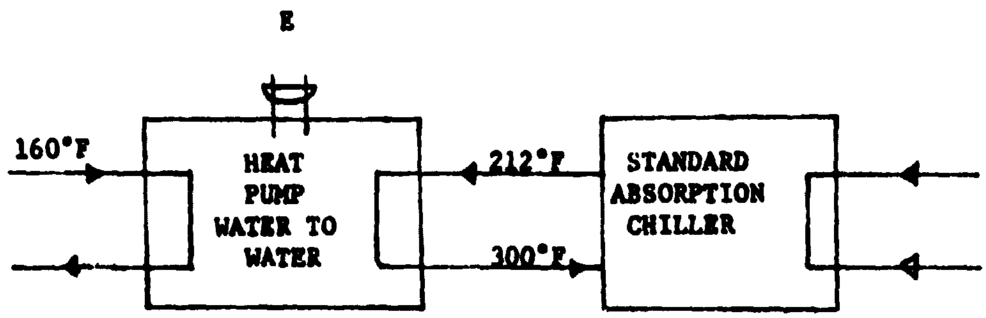
Fan coil units, cabinet units, air handling units, and circulating pumps are all sized to meet the maximum demand. The electric power necessary to drive the auxiliaries is provided by the fuel cell.

4.5 Advanced Components Study

In connection with the exploration of system economics with a variety of available HVAC components, several components likely to be available in the future, and offering improved performance characteristics were examined.

FIGURE 11

HEAT PUMP BOOSTED ABSORPTION CHILLER



Rate of Chilled Water = COP(HP) x COP(AB.CH) x E

= 2.0 x .66 x E

= 1.32 x E

Standard Centrifugal Chiller

Rate of Chilled Water = 4.5 x E

Two significant areas of component improvement specifically related to fuel cell systems are:

- High Efficiency Absorption Chiller
- Battery Storage

High Efficiency Absorption Chiller

Present absorption chillers have a COP (coefficient of performance) of about .67 for normal steam input. Improved absorption chiller COP has been the focus of several development programs designed to stimulate solar cooling. A recent paper study [Ref.5] suggests that a COP of 1.0 can be achieved using ammonia-water in a double effect absorption unit with regenerative heat exchange added between the first and second stage generators. This would reduce the steam demand from 2.3 KG/KW (18 lbs/ton-hour) to 1.5 KG/KW (12 lbs/ton-hour).

An absorption chiller could be developed that would approach the practical limit of efficiency. To estimate this COP one can draw on thermodynamic fundamentals that express the COP of an absorption unit as the product of a power cycle COP and a refrigeration cycle, COP, i.e.,

COP (Absorption) = COP (Power) x COP (Refrigeration)

The technical limit would be:

Technical Limit = .45 x 4.5 (without cooling tower, pumps, fan distribution) = 2.0

Assuming no capital cost increase over a conventional absorption chiller the effect of the double effect - regenerative chiller and technical limit units is shown in Table 15.

Battery

Without electric utility grid connection, backup fuel cell modules are needed. These raise the cost of the system without contributing to the energy savings. In addition, the fuel cells must meet the peak electric demand of the building with additional generating capacity. Electric storage would reduce the fuel cell size requirement and could improve the system economics. For the purposes of this study a simplified model of battery storage has been used. The battery is characterized by a charge efficiency and cost per KWH. In addition, an 11% oversizing has been applied to prevent complete discharge and potential problems that would cause. Several battery types possibly suitable for this application are summarized in Table 16. These include available batteries (Lead-Acid) as well as advanced batteries under development. The range of costs are $50 to $100 per KWH with round trip charge efficiencies from 65 to 75%.

These battery concepts achieve increased capacity with increased cell size. An alternative approach is the Redox concept developed by NASA-Lewis in which a small cell stack is used and the electroytic solutions are actively pumped through it. Charge separating is achieved with a novel ion selective membrane. The electric storage capacity is increased by introducing more fluid in larger storage tanks. A Redox unit cost has been estimated at $50 per KWH exclusive of site preparation, and electric connection costs. We have assumed that the installation cost of this battery would be shared by the fuel cell (electric panel installation) and central storage (pad preparation) installation cost.

An analysis of the effect of battery storage (Redox) was performed with a $50 per KWH cost, a 75% round efficiency, and a 5% operating and maintenance charge. The results of the analysis are summarized in Table 17. These figures reflect an electric control strategy in which an attempt is made to operate the fuel cell at a fixed level. A parametric study was performed to establish the level that produces the lowest LAC, in connection with a series of battery sizes.

TABLE 15

EFFECT OF ADVANCED CHILLER ON SYSTEM ECONOMICS

RETAIL STORE

Absorption Chiller *	System Number	Fuel Cell	Levelized Annual Cost (in $)
Standard (COP = .67)	17BS	B	$264,982
Near Term (COP = 1)	25BS	B	$250,567
Technological Limit (COP = 2)	26BS	B	$232,415

* No increase in chiller cost is assumed for the improved absorption chillers as an upper bound on the possible benefits of advanced chillers.

TABLE 16

BATTERY CANDIDATES

	Round Trip Charge Efficiencies	Cost in Dollars Per KWH (1978): ADL-1980 [Ref. 6]	LBL-1979 (Ref. 7): $/KG	÷	KWH/KG (10^{-3})	=	$/KWH
Lead Acid	70	60	3		42		78
Zinc Chlorine	65	16-43	10.8		100		118
Sodium Sulfate	70	16-32	5.4		110		54
Lithium Iron Sulfide	75	22-32	9.4		110		93

Sources: ADL yet to be published report to DOE on Distributed Energy Systems, 1980.

Energy storage systems for automotive propulsion: 1979, Study - Volume 2
Lawrence Livermore Lab, raised by 10% to 1978 dollars.

The battery will always increase two elements of cost:

- operating and maintenance cost (additional $1,000 to $17,000 per year)
- fuel consumption cost

because the O&M costs are fixed to the KWH output of the fuel cell and not its size, and the battery has a 25% electric energy loss. This situation would be changed in a building with a non-steady thermal demand profile similar to the electric demand but with the peaks occurring in the intervening hours. The battery does <u>lower</u> the system capital cost.

With battery storage, the electric demand on the fuel cell is reduced and so is the thermal discharge. An auxiliary boiler was essential in the apartment to make up the remainder of the domestic hot water demand.

4.6 Custom Components

At the outset of the program we found that steam fired absorption chillers were available in these limited capacity ranges:

Single Effect COP = .66* 10 to 88KW (3 to 25 tons) $/KW = 252
Single Effect COP = .66* 352 to 1355KW (100 to 385 tons) $/KW = 171 to 78
Double Effect COP = 1.1* 1355 to 3730KW (385 to 1060 tons) $/KW = 109 to 80

A 176KW (50 ton) double effect absorption chiller was identified as desirable. A cost per KW of $109 typical of double effect chillers or about 39% more expensive than a comparable size single effect unit was used (Reference Run 14BS). This amounted to about $17,275 added capital cost. As noted in Table 18 the fuel cost savings of $60 per year was not sufficient to offset the added cost, and the LAC increased with the custom component.

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* Not including cooling tower power.

TABLE 17

EFFECT OF BATTERY STORAGE ON SYSTEM LAC

APARTMENT

System	Fuel Cell	Battery	Design Fuel Cell Base Load in KW	Annual Operating & Maintenance Cost (in $1,000)	System Capital Cost (in $1,000)	LAC (in $1,000)
16BA	B	1000 KWH	200	40.4	388	158
9BA	B	Baseline Unit without Batteries	-	39.7	424	162
1AA	A	Baseline Unit without Batteries	-	22.3	356	149
8AA	A	1000 KWH	200	39.2	347	145

STORE

System	Fuel Cell	Battery	Design Fuel Cell Base Load in KW	Annual Operating & Maintenance Cost (in $1,000)	System Capital Cost (in $1,000)	LAC (in $1,000)
27BS	B	3000 KWH	350	60.1	723	296
13BS	B	Baseline Unit without Batteries	-	53.0	732	249

TABLE 18

EFFECT OF A CUSTOM 176 KW (50 TON) DOUBLE EFFECT ABSORPTION CHILLER ON PERFORMANCE

(RETAIL STORE)

Case	Reference Run	Absorption Chiller Size	COP	Levelized Annual Cost	Capital Equipt. Cost	Annual Fuel Cost
Baseline	9BS	176KW	.6	$250,686	$742,354	$72,472
Custom Double Effect Chiller	14BS	176 KW	1.0	$250,392	$740,835	$72,531

5. FINDINGS AND RECOMMENDATIONS

The purpose of this study is to evaluate the impact of available and soon-to-be-available heating, ventilating and air conditioning components on the overall on-site integrated fuel cell economics, and to identify policy and technical alternatives that could improve the economics and customer-acceptance of these systems.

A comprehensive analysis of numerous system designs discussed in the forgoing chapters identified promising system designs and the sensitivity of the system performance to key design variables. In this next chapter we shall summarize the findings and make recommendations based on the sensititivity analysis.

5.1 System Performance

Components selections based on the analysis presented in Chapter 4.0 led to system designs matched to the building load and the fuel cell. The systems with the lowest levelized annual cost* for each fuel cell, with and without boiler backup are summarized in Tables 19 and 20. System diagrams of all 10 systems are given in Volume II. A system diagram of the lowest levelized annual cost system (1AA)and a competitive conventional electric system are given in Figures 12 and 13 for illustration.

Using levelized annual cost as the figure of merit, all of the fuel cell based systems in the residential application are better alternatives than the all electric conventional system, but none are better than the conventional gas heated/electrically cooled building. The fuel cell systems have 3% and 12% higher levelized annualized costs than the gas heated building for the economic parameters given in Section 4.2. To test the

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* Levelized Annual Cost (LAC) is the total owning and operating cost of the system including interest on borrowed capital, fuel cost, insurance and maintenance.

TABLE 19

RESIDENTIAL SUMMARY

SYSTEM NUMBER [1]	SYSTEM	AUXILIARY BOILER BACKUP	LEVELIZED ANNUAL COST IN $1,000 [2]	INTERNAL RATE OF RETURN [2]	CAPITAL COST IN $1,000 [2]
2A	Conventional Electric	-	175	Base	174
3A	Conventional Gas	-	144	-	192
1AA	21-21KW Fuel Cell A	-	149	34.0%	355
4AA	21-21KW Fuel Cell A	Boiler	150	32.0%	365
9BA	21-21KW Fuel Cell B	-	162	23.9%	424
10BA	21-21KW Fuel Cell B	Boiler	163	23.4%	431
5CA	5-129KW Fuel Cell C	-	154	26.3%	434
6CA	5-129KW Fuel Cell C	Boiler	155	25.6%	441

1 - Components comprising the system are given in Section 4.4 - Table 4A thru 4F.

2 - See Section 4.2 for an explanation of Levelized Annual Cost and Internal Rate of Return Compared to Conventional Electric. Section 3 of Volume 2 provides the complete financial analysis of each system.

TABLE 20

RETAIL STORE SUMMARY

SYSTEM NUMBER[1]	SYSTEM	AUXILIARY BOILER BACKUP	LEVELIZED[2] ANNUAL COST IN $1,000	INTERNAL[2] RATE OF RETURN	CAPITAL COST[2] IN $1,000
2S	Conventional Electric	-	194.5	Baseline	243
1S	Conventional Gas	-	188.9	-	258
4AS	14-61KW Fuel Cell A	-	226.4	5.9%	584
5AS	14-45KW Fuel Cell A	Boiler	258.0	Negative	585
13BS	14-57KW Fuel Cell B	-	249.0	2.9%	732
17BS	14-44KW Fuel Cell B	Boiler	264.9	Negative	671
4CS	6-143KW Fuel Cell C	-	223.0	10.7%	692
5CS	5-144KW Fuel Cell C	Boiler	239.0	Negative	658

1 - Components comprising the systems are given in Section 4.4 - Tables 4A through 4F.

2 - See Section 4.2 for an explanation of Levelized Annual Cost and Internal Rate of Return compared to Conventional Electric. Section 3 of Volume 2 provides the complete financial analysis of each system.

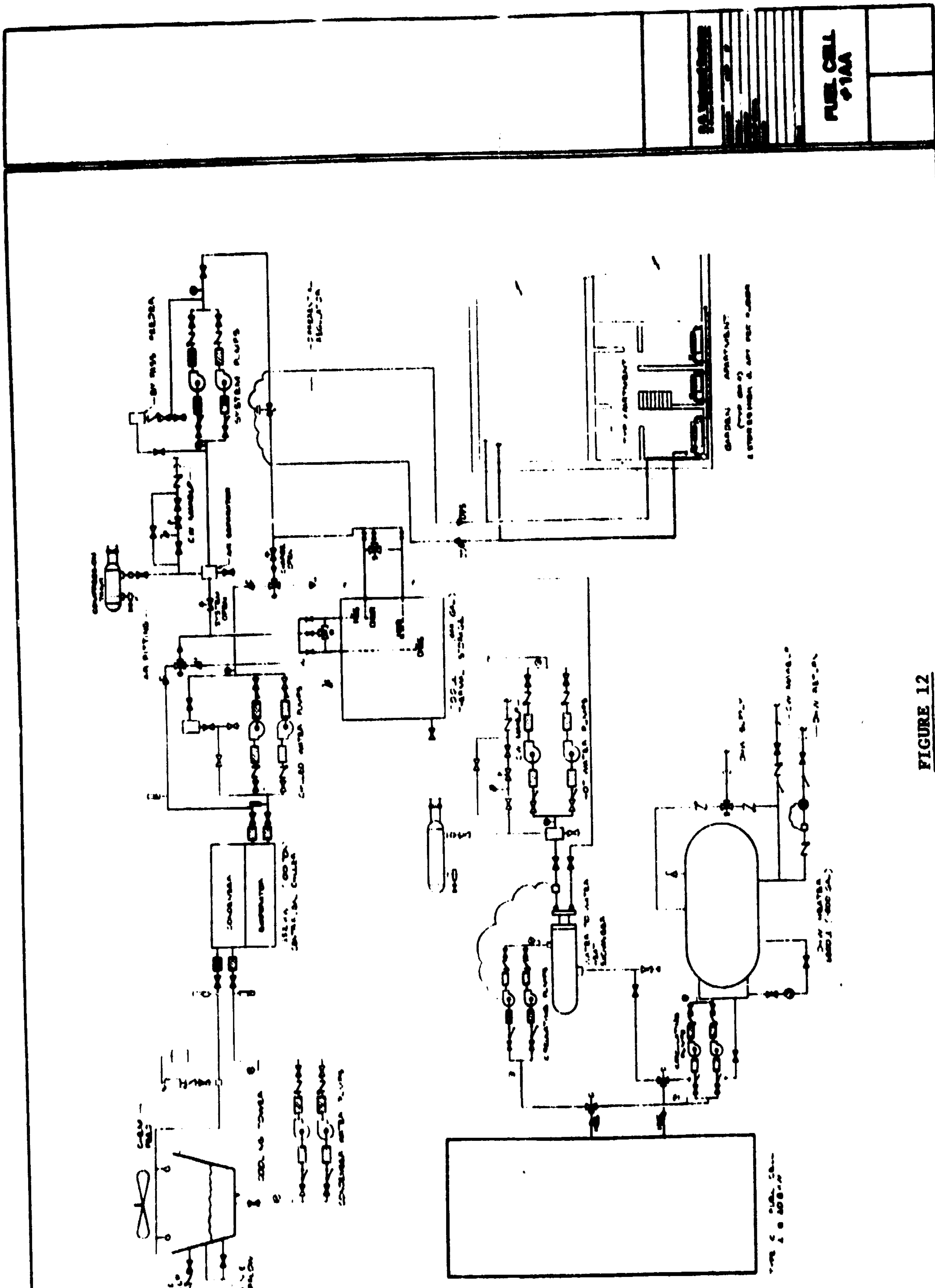

FIGURE 12

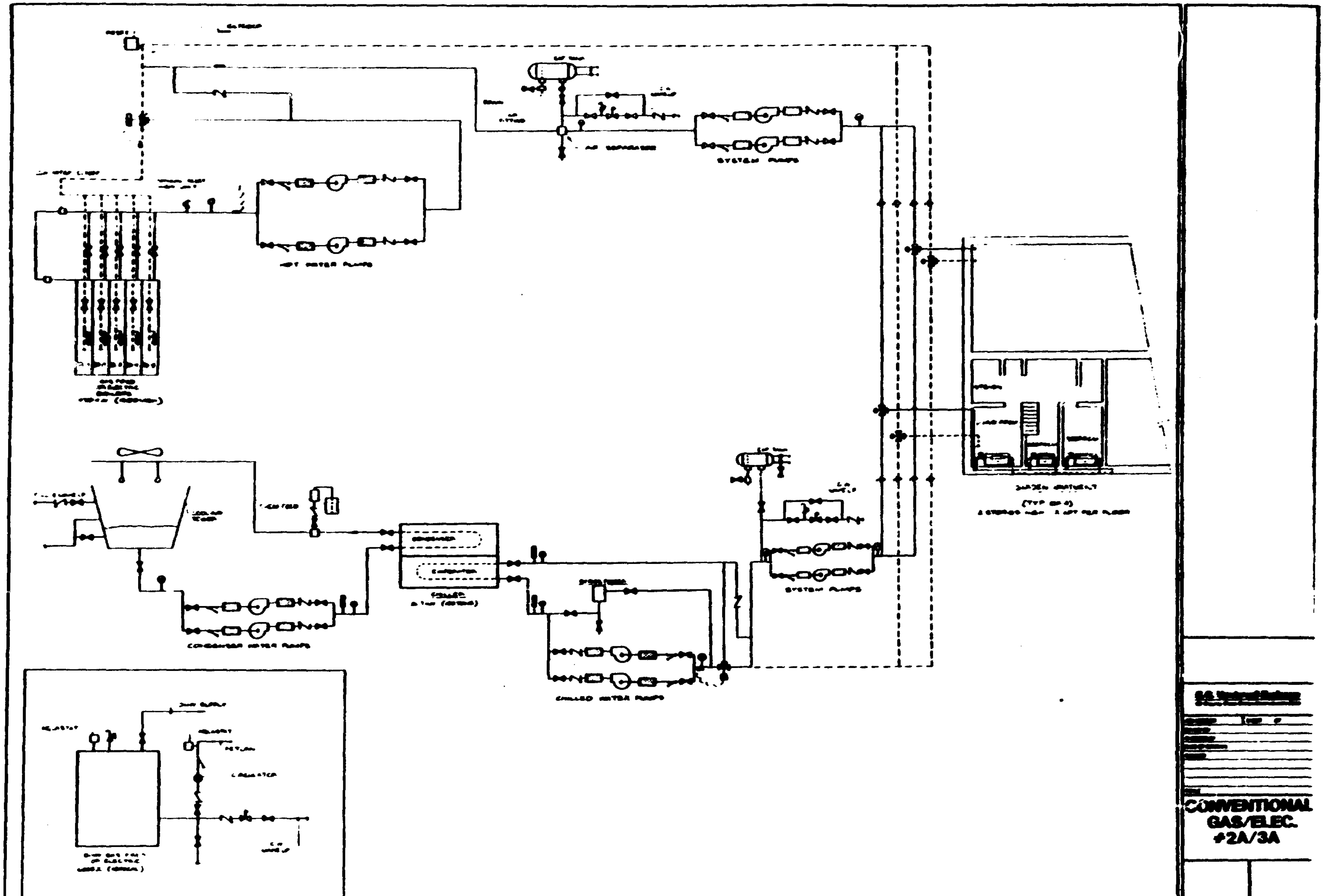

FIGURE 13

credibility of these differences a brief sensitivity analysis was performed on the key economic parameters. The baseline values of the variables were:

- System Reliability - A 3 hour per 10,000 hour maximum outage criteria was used throughout the study.

- Fuel Cell Cost - The capital cost of the fuel cells provided by NASA are summarized in Table 2.

- Cost of Capital - A 20% before tax cost of capital was used.

- Fuel Escalation Cost - .6% electricity; 2.4% gas.

The results of the sensitivity analysis are summarized in Table 21.

As this table shows, fuel cell cost and cost of capital have the largest effect on the levelized annual cost. A 25% variation in either of these values produces a 2 to 4 percentage point change in LAC savings. The effect of a 25% change in electric escalation cost raising it to .75 results in a 1 to 2 percentage point savings in LAC. As the electric escalation cost though is still but 1/3 of the gas escalation cost, substantial increases in the electric escalation cost could be envisioned for the future when gas costs reach equivalent electric prices. Marginally competitive systems (1AA, 5CA) become clearly competitive with either a 25% reduction in fuel cell capital cost or cost of capital (from 20% to 15% cost of capital).

These results reinforce the importance of developing consistent and credible fuel cell capital costs for feasibility analysis. In addition, attention should be given to qualifying the fuel cell system for conventional commercial loans at or near the prime lending rate (less than 15%), by convincing the financial community of the demonstrated reliability and fuel cost savings of the on-site fuel cell system. Projections of gas and electric escalation rates should be updated and incorporated in future studies.

TABLE 21

ECONOMIC PARAMETERS SENSITIVITY ANALYSIS
PERCENTAGE SAVINGS IN LAC OVER CONVENTIONAL GAS

Building		Residential			Store		
Fuel Cell		A	B	C	A	B	C
System		1AA	9BA	5CA	4AS	13BS	4CS
Economic Parameter	Change						
Baseline Economic Parameters	N/A	-3	-12.5	-6.9	-19.8	-32.4	-18.6
System Reliability	x1/10					-29.9	
Fuel Cell Cost	-10%	-1.7	-10.0	-4.7	-17.2	-28.2	-15.4
	-25%	1.0	- 6.1	-0.8	-13.2	-22.7	-10.8
Cost of Capital	-10%	-2.1	-10.7	-5.0	-18.0	-29.1	-15.6
	-25%	0.0	- 7.8	-1.8	-15.4	-25.0	-11.5
Electric Escalation Cost	+10%	-3.3	-12.4	-6.9	-19.4	-31.3	-18.0
	+25%	-2.9	-12.0	-6.6	-18.8	-30.7	-17.4

* Reliability is defined as hours out outage per 10,000 hours of operation. The baseline outage was 3 per 10,000 a reduction in reliability by 10 raises the outage to 30 hours per 10,000.

5.2 Component Analysis

5.2.1 Sensitivity Analysis

The effect of component selection on the two key measures of performance:

- Energy Cost Savings
- Levelized Annual System Cost

was examined in a sensitivity analysis. Table 22 summarizes the effect of component selection on energy cost savings and Table 23 gives the effect on levelized annual cost.

5.2.2 Fuel Cell

Though its impact is dependent on the type of financing and ownership the fuel cell power plant cost is the single most important component cost in determining the attractiveness of on-site fuel cell systems. Numerous cost projections have been made for the different types of fuel cell power plant designs and these have been reflected in the power plant costs used in this study. The average (50KW) fuel cell power plant installed cost is between $16,000 and $23,000 ($300 per kilowatt) in the systems analyzed in this program. These costs are designed to reflect expected unit costs in production volumes of approximately 10,000 to 100,000 units per year [Reference 8]. Today's prototype unit costs are estimated to be approximately 1,500 dollars per kilowatt representing a substantial challenge to reduce the fuel cell unit costs [Reference 8]. Achieving the fuel cell power plant cost levels projected for the future should be considered a priority program goal. In addition, reducing the added operating and maintenance cost of $10,500 per year for the fuel cells would have a substantial effect on the annual operating cost (about $50,000 per year) of the system, particularly when load leveling thermal or electric storage is employed. The operating and maintenance costs are based on delivered KWH and while load leveling will reduce the installed capacity required the annual KWH of the fuel cell is greater as was shown in Table 17 for battery load leveling.

TABLE 22

PERCENTAGE ANNUAL ENERGY COST SAVINGS

(Savings are Positive)

Component	Change	Residential	Store
Fuel Cell	Conventional Gas to Fuel Cell B	+ 51.3	+ 71.1
	From B to either C or A	- 15.4	- 21.9
Central Thermal Storage	0 to Optimum	+ .4	+ 1.9
	Eliminate Jacket Losses		0
Auxiliary Boiler	0 to Maximum*	- 5.1	- 33.8
	High Efficiency Modulating	+ 10.1	+ 1.8
Absorption Chiller	0 to 10% of Cooling Load	+ 0.6	+ 1.6
	Advanced Maximum Efficiency		+ 12.8
Battery Storage		+ 1.2	- 16.0

* 100% of cooling is met by the auxiliary boiler and absorption chiller.

TABLE 23

PERCENTAGE SAVINGS IN LEVELIZED ANNUAL COST

Component	Change		Residential	Store
Fuel Cell	B to A or C		+ 8.7	+ 9.9
Central Thermal Storage	None to Optimum Size		+ 1.0	+ 3.4
	Eliminate Jacket Losses			+ 0.1
Auxiliary Boiler	0 to Maximum		- 7.3	- 14.1
	Standard to High Efficiency		- 1.0	+ 3.7
Absorption Chiller	% of Cooling Load	0 to 10%	- 2.8	+ 1.0
		10 to 100%	- 4.9	- 6.4
Domestic Hot Water Storage	Double Size from 2 Hour Minimum		- 3.8	- .4
Heat Exchangers	Eliminate Hot Water Heat Exchanger		+ .003	+ .004
Battery Storage	0 to 1000KWH		+ 2.7	- 15.9
Automated Energy Management System	Reduce Peak Electric Demand		+ 5 to + 10 (Rough Estimate)	

Fuel Cell C offered the largest annual energy savings (Table 24) of the three fuel cells considered in both the retail store and the garden apartment, and had the best overall levelized annual operating cost in the store because of its ability to produce steam for cooling and its lower projected capital cost. Both hot water and steam can be used effectively in buildings with substantial domestic hot water and heating loads. A steam source fuel cell (C) is preferred in the retail store because steam can be inexpensively ($1,200 maximum cost heat exchanger) converted to hot water whenever needed, and steam can more effectively power absorption chillers. Hot water absorption chillers are more expensive than steam fired chillers (360 $/KW vs 252 $/KW) and have lower efficiencies.

Fuel Cell A was the best pick for the apartment because steam is not as critical to the apartment and Fuel Cell A is available in 20KW size modules while Fuel Cell C has a 100KW module minimum. The electric load could be matched better with the smaller modules. Fuel Cell B had the highest unit cost and lowest efficiency and was not the pick for either building. As shown in Table 23, choosing Fuel Cell A or C over B saves 9 to 10% levelized annual cost.

In general, Fuel Cell C (all steam, advanced technology) is preferred because of its lower cost and higher overall efficiency (Table 2). However it is limited to a 100KW module minimum and this is a distinct disadvantage in a stand-alone system where redundancy is required. Fuel Cell C also has the highest outage rate. These two factors combine to cause the systems with Fuel Cell C to require about 46% higher capacity than the other fuel cells in the apartment, which are available in more optimal 20KW modules. Fuel Cell A, the next lowest cost type then becomes the best choice for the apartment which does not require steam for the chillers. We recommend further attention to be given to the development of lower <u>minimum</u> modules sizes for the advanced fuel cell when designed for stand-alone systems requiring redundancy and to lower the forced outage rate to that of the other fuel cells.

TABLE 24

ANNUAL FUEL (NATURAL GAS) COSTS

in 1978 Dollars

FUEL CELL	RETAIL STORE ANNUAL FUEL COST	RESIDENTIAL BUILDING ANNUAL FUEL COST
Conventional Electric	129,030	122,360
Conventional Gas	119,910	85,190
A	75,610	48,800
A with auxiliary boiler*	101,170	49,450
B	73,040	49,500
B with auxiliary boiler*	96,080	49,750
C	57,790	41,460
C with auxiliary boiler*	77,030	42,340

* Auxiliary boilers discussed in Section 4.4.2 were used to reduce the demand on fuel cells in an attempt to reduce total system installation cost.

Cooling fans are integral to the fuel cell and manage waste heat not used by the HVAC system. These fans and motors add cost to the fuel cell both as purchased parts and as they require additional cabinetry and mounting hardware. Based on our analysis we recommend that further studies consider eliminating a fraction of these cooling modules as they are redundant with the cooling tower capacity. During high thermal demand periods the cooling modules are idle and during low thermal demand periods there is probably spare HVAC cooling tower capacity to handle some of the fuel cell load.

5.2.3 Building Selection

Buildings such as the garden apartment with relatively high domestic water usage and flat load profiles are more conducive to stand-alone fuel cell applications than buildings such as the retail store which is dominated by high non-steady cooling demands. Other buildings such as:

- Hospitals
- Restaurants
- Fast Food Stores
- Central Kitchens
- Food Preparation Centers
- Factories
- Process Applications
- Food Processing Plants

may be even more attractive applications.

Measuring the desirability of a building type by simple figures of merit of the integrated ratio of thermal to electric demand to the fuel cell thermal to electric output are useful initial screening measures. However, it quickly loses its relevance when the system designer is attempting to reduce the annualized system cost below the level of conventional system. With the peak load imposed by the cooling demand and the cost penalty of absorption chillers, the integral thermal to electric measure can be misleading. The steadiness of the demand is as important as the matching of the thermal to electric ratio. Selection of approprivate buildings for on-site fuel cell systems should be predicated on the basis of the quantity and temperature of thermal energy and the steadiness of the thermal and electric loads. We recommend that a figuire of merit be developed reflecting these measures of adaptability in fuel cell systems. The approach we recommend is to hypothesize generic load profiles that characterize major building types and test the system performance of the building in the system computer model. A series of thermal and electric relations can be developed which point to the best type of buildings for on-site fuel cell systems.

5.2.4 Thermal Storage

Thermal storage for domestic potable hot water is clearly necessary as a result of the non-steady nature of water draws. In general, the amount of thermal storage is equal to a few hours of average hot water withdrawal.

Large central thermal storage for space conditioning should be considered when the building load is dominated by a non-steady function such as space cooling. Though the store requires about twice the installed fuel cell capacity as the apartment, (about 700KW versus 400KW) the optimum size of thermal storage for the retail store is about 100 times greater than in the garden apartment due to the non-steady nature of the building load for systems without electric grid connection. The amount of thermal storage needed is likely to change if grid connection is provided.

This study clearly indicates that cool water thermal storage is preferred over high temperature storage for the absorption air conditioner. Cool storage is highly desirable in connection with absorption chillers independent of remainder of the system. Cool storage ($45,000) can reduce the absorption chiller capital cost in the store by about $36,000 and the fuel cell size by $38,710 saving a net $23,000 of capital equipment.*

* The equipment savings is $30,000 but there is an additional $7,000 of piping, pumps and controls cost for the storage.

Central thermal storage (cool storage in the summer and warm storage in winter) offers savings of .4 to 2% in energy (Table 22) and 1 to 4% in levelized annual cost. The main benefit is a reduction in fuel cell and chiller installed capacity.

Although improved thermal storage insulation would further reduce fuel consumption it would not appear to be an area needing attention. Fully eliminating thermal storage jacket losses for the large 378,540 liters has the effect of reducing the levelized annual cost by .02% from $250,382 to $250,319 (System 13BS and 30BS).

5.2.5 Absorption Chillers

For nearly all of the systems considered in the retail store, an optimum partitioning of 10% absorption chiller capacity to 90% electric chiller capacity was indicated (Table 10, Section 4.4.3). This arises from the amount of waste heat available, the difference in chiller capital cost per ton and the large difference in COP between these two units.

No absorption chillers were indicated for the apartment. The available steam could be best used to meet the steady, high domestic hot water demand.

Improving absorption chiller efficiency at no change in cost will save between $17,000 to $34,000 in levelized annual cost (LAC). Achieving the higher COP levels of advanced absorption chillers will benefit fuel cell systems and is strongly encouraged.

A substantial part of the chiller cost is in the cooling tower and this cost could possibly be decreased slightly through system integration with the heat rejection equipment contained in the fuel cell. By judicious system design, the absorption chiller and fuel cell could share the same heat rejection cooling tower equipment and reduce installed costs.

5.2.6 Auxiliary Boilers and Air-to-Water Heat Pumps

Auxiliary boilers can reduce the levelized annual cost when there is substantial hot water or heating demand in excess of the thermal discharge of the fuel cell when meeting the base electric load. Operation of the auxiliary boiler to power an absorption chiller to displace electric demand for operating the electric chiller is not indicated to be cost effective. The problem with this approach lies in the capital cost of absorption chiller and not in the auxiliary boiler. The additional installed absorption chiller capacity to be powered by the auxiliary boiler and fuel cell is a substantial capital cost item and offsets the minor cost savings from reducing installed fuel cell capacity. Auxiliary boilers should be considered when there is a substantial heating demand beyond the thermal energy available from the fuel cell to meet the base electric plus chiller demands.

Air-to-water heat pumps were not included as a balance-of-plant component because it was felt that they offered no intrinsic advantage to the fuel cell basic system and as such would benefit the conventional building equally. This argument can be justified in light of the effect of the auxiliary boiler on the system. The heat pump essentially offers a very high heating efficiency to both the conventional and fuel cell system. However, there is sufficient hot water and steam generated by the fuel cell for heating to make the heat pump energy savings contribution relatively insignificant. The primary function of the heat pump would be in the cooling mode where it would have to compete with a low cost high efficiency electric chiller supported by an absorption chiller sized to use waste heat from the fuel cell. Substituting a heat pump for an optimized electric/absorption chiller combination is likely to increase the levelized annual cost of the fuel cell based system and reduce the levelized annual cost of the conventional system. Confirmation of this argument should be undertaken as part of future studies.

5.2.7 Battery Storage

Battery storage (at $50 per KWH) for stand-alone on-site fuel cell systems offers a reduction in levelized annual cost. Some of the battery storage benefit is offset by the fixed charge (tase on KWH output which is not reduced) for the operating and maintenance cost of the fuel cell. Though the net system capital cost reductions range from $9,000 to $36,000 (including the added $50,000 for battery storage), the fuel cell operating and maintenance (O/M) charge increases range from $1,765/year to $2,170/year based on the present technique for estimating fuel cell O/M costs as a function of delivered KWH. As recommended earlier (Section 5.2.1), new and reduced O/M charges for the fuel cell should be sought. These charges should be changed to reflect the benefit of load leveling on operating/maintenance costs for the fuel cell.

If there is a necessity to maintain the stand-alone power plant feature (no electric grid connection) then battery storage integration with the fuel cell power plant should be considered. Efforts should be directed at developing shared electric control panels for the battery and fuel cell, and the effect of battery storage on fuel cell operating and maintenance costs should be examined. More refined battery installation costs should be developed for this specific application.

5.2.8 Automated Energy Management Systems

Automated Energy Management Systems (AEMS) should be considered for all fuel cell applications. Typically, an AEMS system will cost from $5,000-$30,000 depending on the number of devices it must control, and it will provide:

- Peak load shedding
- Optimal start/stop of HVAC equipment
- Enthalpy controlled ventilation

The peak shedding is done a predetermined priority use basis and can substantially reduce the peak electric demand. A conventional HVAC system would benefit from load shedding by reducing the demand charge but the net savings would probably not be as much as the on-site fuel cell system. In this study no demand charge was made against the conventional system and the net effect of an AEMS would be the substantial capital cost savings to the fuel cell system as the conventional and fuel cell systems would probably benefit equally from the optimal start/stop and enthalpy control function. If the AEMS system could limit the apartment to a 200KW base load (System 8AA) a $68,000 savings in fuel cells could be achieved.

We recommend that a study be conducted with AEMS/fuel cell systems accounting for the demand charge on the conventional systems. We regard this as a high priority recommendation as it could substantially improve relative fuel cell economics.

5.3 Business and Policy Recommendations

5.3.1 Ownership and Financing

Power plant ownership is a central question to the future of fuel cell utilization. Ownership could be in the hands of a number of entities not limited to the following:

- Gas and/or Electric Utility
- Building Owner (if not the Developer)
- Developer
- Separate Leasing Corporation

The ownership will effect many of the aspects of the system including the issue of utility grid connection and financing of the power plant as discussed in this and the following section.

5.3.2 Utility Ownership

The fuel cell power plant could be owned by the local gas or electric utility and along with potential benefits a number of complex issues arise. The TARGET (Team to Advance Gas Energy Transformation) project identified [Reference 9] gas utility ownership as the superior ownership alternative.

Utility ownership may broaden the financing options to the builder and would certainly lower the capital investment requirement of the building owner. The utility would gain revenues from the operating and maintenance as the rental income on the equipment. However, these advantages may be offset by other business considerations:

- Electric grid backup
- Revenues to the builder (5.3.3)

Gas utility power plant ownership makes electric grid connection backup arrangements unclear. The public policy and financial risk implications of such an arrangement should be investigated.

A grid connected electric utility owned fuel cell power plant concept was examined by Westinghouse [Reference 11] in which 10 different strategies for load shedding were considered. Their findings indicate that a grid connected fuel cell system will benefit the electric utility if on-site generating strategies are employed that improve the utility load factor. Westinghouse suggests that electric utility ownership of the fuel cell power plant would encourage grid connection, as the fuel cell would be managed by the electric utility. This arrangement would have the benefit of consolidating the system-wide and local cost/benefit of the fuel cell in one entity - the electric utility. Credits for reduced central plant generation, and transmission cost would be figured into the monthly utility charge along with operating and maintenance cost.

The benefits of these types of arrangements on the building owner will be minimal. The building owner would pay energy costs to the utility and pass them along to the occupants and unless these energy costs are lower than the local cost of energy available on the grid the building owner makes no profit on the system and has no incentive to take any risk in connection with it.

Alternatively the utility could retain ownership of the fuel cell and lease it to the developer. In this arrangement the developer could benefit from the control of the power plant but would not take the same level of risks (see Section 5.3.4 - Risks) as an owner. One area of concern to the developer is the long-term availability of natural gas needed for the fuel cell. The uncertainty of natural gas supply and cost coupled with future regulations setting the priority of gas users makes an investment in the fuel cell a high risk undertaking. Innovative leasing arrangements could abate some of these risks.

5.3.3 Developer Ownership

The developer could own the power plant and work the operating cost and capital charge into the rent basis of the building. The developer would assess the cost of the plant, add a profit and compare this charge to the local electric utility charge. If the fuel cell cost plus overhead and profit are competitive then this would be part of the advertised rent base when space is being sold. While the developer must perform the financial analysis, a reliable and relevant set of financial data must be made available. This should be a principle function of future fuel cell development work.

A developer of a retail store, garden apartment or other medium size building would view the on-site fuel cell power plant as a financial risk (Section 5.3.4) independent of ownership and whether or has electric utility backup. It is a developing technology and its presence on-site, may bring unforeseen problems. In this light, a developer is likely to accept the risk if there is a profit to be gained. Utility ownership of the fuel cell would eliminate the potential for profit, and lessen the attractiveness to the developer. Utility ownership is not clearly the superior approach in all cases, and is likely to be the less attractive approach for most large buildings (over 100,000 sq.ft.).

The practicality of developer ownership can be seen more clearly when the fuel cell capital cost is given a percentage of the HVAC cost. Table 25 shows that the fuel cell is about 30% of the HVAC capital cost, which is even a smaller fraction of the entire building project cost. Therefore, the fuel cell cost represents a relatively small portion of the total project cost.

From the developer standpoint there are three distinct aspects to a financial analysis of products like fuel cells:

- The actual cash-flow attributable to the product
- the means, and cost, of financing the project
- and, the options for changing either the cash-flow or the financing cost to encourage the project.

For a comprehensive understanding of a projects financial implications, it is important to keep all three of these aspects separate. Very different analytic methods and criteria are used in evaluating projects in different classes of buildings and the implications or appropriateness of any scheme can only be determined by the developer from the basic cash-flows and financing methods.

Cash Flows

Typical cash-flows involved in analyzing real estate and energy related projects are:

- Initial incremental capital cost
- Energy saved BTU's and dollars
- Incremental operating costs (excluding financing costs)
- Repair and maintenance costs (incremental)
- Property taxes (if applicable) (incremental)
- Depreciation (incremental)
- Income Taxes (incremental)
- Investment Tax Credits (incremental)

TABLE 25

POWER PLANT SHARE OF COST

		System Capital Cost	Piping *	Fuel Cell Cost	Fuel Cell as a % of Total
1AA	Apartment	185,365	180,500	170,500	32%
4CS	Store	314,191	651,000	378,662	28%

* Although piping costs are a large fraction of the total system, the comparative economics analysis and all Levelized Annual Costs reported in this report (Volume II, Chapter 3) do not include the piping cost. Only about $14,000 of piping cost may be attributable to the system designs considered in this study and the remaining 92 to 98% of the piping cost remains constant and is considered as though it were part of the invariant building structure cost.

Care should be taken with income taxes, investment tax credits and depreciation as they can differ substantially between investors, types of buildings and types of projects.

Financing Methods and Costs

There are two basic methods of financing this type of project, excluding outright purchase by the owner using existing equity; the options are:

- Leasing from a utility or leasing company
- Purchasing with a bank loan

Under leasing, certain of the tax and depreciation benefits are transferred to the lessor and some financial benefits are obtained by the lessee, whose requirement for up front capital is eliminated. These can have a substantial effect on the economic attractiveness of the project. Within a purchase, there are a number of debt versus equity mix assumptions which effect the after tax return to the developer.

It is likely that the conventional sources of development financing will view the power plant as outside of the normal rentable space and are likely not to provide a loan to the developer for the power plant. Historically the lender looks at the base rent and would not include the extra cash flow from the power plant in evaluating the loan. The developer may have to use equity or look for a higher interest rate loan. This barrier may be overcome by subsidies.

- Financing cost subsidies
  - interest subsidies
  - loan term alterations

- Cash-flow subsidies
  - tax deductions or credits
  - accelerated depreciation
  - annual operating subsidies

Each of these different incentive techniques will show different results depending upon the type of financing method employed and the type of building owner involved.

5.3.4 Risks

The developer views the risk of a fuel cell based power plant in its effect on the entire building project. If the fuel cell fails it would threaten the entire project affecting tens of millions of investment dollars. Until the fuel cell is shown by demonstration to be totally reliable a developer would require a complete backup capability - full power grid connection. This would greatly reduce the attractiveness of the system since the utility would charge a substantial monthly standby charge to the project.

Increased liability insurance could result from the fuel cell installation even if the fuel cell is technically as safe as a conventional boiler. The increased cost comes from the limited historical experience with fuel cell installations which is likely to cause insurance companies to view the equipment as a higher than normal risk.

Another risk identified earlier (Section 5.3.2) is the availability of fuel. This can be somewhat mitigated as the multi-fuel capability of the fuel cell is expanded. However, in the near term, the dependence on natural gas raises the risk of supply interruption.

Finally, developers are exposed to the risk of not negotiating satisfactory electric grid backup with electric utilities that are not also providing natural gas.

5.3.5 DOE Policy

The Department of Energy policy regarding 40KW on-site fuel cell systems will have a direct bearing on most of the issues identified in this chapter. The questions of fuel cell development and balance-of-plant component development can be accelerated with DOE involvement and sponsorship of programs. Fuel cell ownership, particularly with utility ownership, will involve DOE regulatory decisions of considerable importance. Government tax incentives could make private ownership of fuel cell power plants more inviting to the developer or building owner. Government support to utilities or private companies that would own and operate the power plants for the building owner should also be considered. These areas will require additional analysis before a firm policy recommendation could be developed for DOE.

DOE should establish a clear, long-term fuel supply scenario for the fuel cell. The first generation fuel cell will be based on high priority natural gas which is likely to cause any investor great concern. Commercial building developers have confronted the complex and volatile issue of natural gas availability for a number of years and are reluctant to make large capital investments in equipment with a 30 year lifetime which is dependent on a specific fuel source with an uncertain future. DOE must offer the investor a reasonable level of security that fuels adequate to power the fuel cell will be available for the near future.

Lastly, a field demonstration of 10 to 100 large projects using on-site fuel cells is needed. A developer or investor requires proven reliability and fuel cost savings before they would support a fuel cell installation.

5.3.6 Summary Recommendations

The following section highlights the key technical, financial and policy recommendations derived in this study. Most of these recommendations are discussed in detail in the foregoing section, some are corollaries or extensions and are presented without further development.

Fuel Cells

- Concentrate on the development of accurate installed cost projections for the fuel cells.

- **Develop cost saving designs by sharing housing facilities, controls and cooling towers with the BOP components.**

- **Continue to develop advanced steam source fuel cells and target lower minimum module size (to the 20KW level) for application in stand-alone systems requiring redundancy.**

Building Selection

- **Examine internal rate of return for fuel cell systems in a number of building types in different climatic zones.**

- **Develop a figure of merit reflecting: building thermal to electric load ratio and steadiness of load for use in selecting appropriate sites for fuel cells.**

Auxiliary Boilers

- **Auxiliary boilers are not indicated as beneficial for any system.**

Automated Energy Management Systems (AEMS)

- Conduct a study with an AEMS/fuel cell system in comparison with a standard building with an AEMS unit.

Battery Electric Storage

- For stand-alone systems requiring reliability comparable to grid connected system, battery storage may be beneficial. More accurate battery/system costs should be developed.

Heat Pumps

- As air-to-water heat pumps gain in market acceptance and become an accepted element of standard building, HVAC systems, the air-to-water heat pump should be factored into the fuel cell system.

- Evaluate the comparative levelized annual cost of air-to-water heat pumps for both fuel cell and conventional systems.

Thermal Storage

- Thermal storage for domestic hot water is necessary and can be met with minimal volume.
- Large central cool storage should be considered for all buildings dominated by the cooling load. Hot storage (pressurized) for absorption cooling is not recommended.
- Techniques for properly sizing thermal storage should be developed.
- Improved insulation technology is not necessary.

Absorption Chillers

- Extreme care should be given to the proper sizing of the absorption chillers - electric chillers ratio.
- Development of high efficiency absorption chillers (1.8KW/ton) is recommended.
- Absorption chillers are not recommended for all systems. Apartment cooling loads are best met with electric chillers only.

Fuel Cell Ownership

- Develop meaningful financial criteria to determine the desirable ownership strategy based on real building developer/builder business goals.

- Develop cost/benefit analysis of different ownership scenarios with and without electric utility grid connection.

Financing Recommendations

- Focus efforts on qualifying fuel cell system for conventional commercial loans at or near the prime rate (less than 15%).

- Develop grid connected system economics considering:
  - fuel cell redundancy
  - full backup

- Evaluate cash flow in several locations using local gas and electric rates and develop a system portfolio designed for the building developer.

- Develop consistent and credible fuel cell installed costs.

6. REFERENCES

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