NASA Technical Memorandum 78996

FUEL CELL ON-SITE INTEGRATED ENERGY SYSTEM PARAMETRIC ANALYSIS OF A RESIDENTIAL COMPLEX

(NASA-TM-78996) FUEL CELL ON-SITE INTEGRATED ENERGY SYSTEM PARAMETRIC ANALYSIS OF A RESIDENTIAL COMPLEX (NASA) 25 p HC A02/MF A01 CSCL 10B
N79-11955
Unclas
G3/85 36985

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TECHNICAL PAPER presented at the
Fuel Cell Workshop
sponsored by the Department of Energy
Sarasota, Florida, November 14-17, 1977

FUEL CELL ON-SITE INTEGRATED ENERGY SYSTEM

PARAMETRIC ANALYSIS OF A RESIDENTIAL COMPLEX

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E-9780

SUMMARY

Energy conservation via the use of integrated energy systems is attracting renewed interest as a means of extending the supply of fossil fuel. An integrated energy system satisfies all of the energy requirements of a specific application from one powerplant. In this paper a phosphoric acid fuel cell powerplant provides all of the electricity required by a large apartment complex and by-product heat is recovered to help in providing for the thermal requirements of the complex. Additional thermal requirements are satisfied by electrically driven devices such as heat pumps, compression chillers and resistance heaters. In this kind of system the energy contained in the fuel is used to the maximum extent.

Several parametric combinations of fuel cell powerplant, state-of-the-art on-site energy recovery systems and building locations were analyzed and an annual fuel requirement was calculated. The range of phosphoric acid fuel cell operating characteristics used is representative of units being developed for commercalization in the mid-1980's. The fuel cell fuel is natural gas. The on-site integrated energy system (OS/IES) contains energy conversion equipment including combinations of compression and absorption chillers, heat pumps, electric resistance heaters and thermal storage. The application selected for this study is an 81-unit garden apartment complex that requires electricity (for lights, appliances, and air handling motors), space heating and cooling, and domestic hot water. The apartment complex was sited in four locations to study climatic effects.

In addition to calculating the annual fuel requirement for several OS/IES combinations, the fuel cell breakeven cost was calculated for one specific system.

The energy analysis shows that even in integrated energy systems that use by-product heat rather than reject it to the environment, electrical efficiency cannot be traded off against thermal efficiency without paying a penalty in system efficiency. This is because those services that can be provided by either electricity or by-product heat (i.e. space heating/cooling or water heating) can be delivered more economically by electrically driven devices than by thermal means. Electrically driven devices such as heat pumps and compression chillers have a mechanical advantage (COP > 1) that allows them to provide a thermal output greater than the electrical input to the device. Thermally driven devices always have a thermal output less than their thermal input.

The energy analysis also shows that OS/IES component choices have a major influence on annual fuel consumption.

The economic analysis shows that for one case a $50/kW capital cost premium can be absorbed for a high-efficiency fuel cell. This is about 10 percent of the powerplant cost.

INTRODUCTION

Phosphoric acid fuel cell technology has progressed in recent years to the point where powerplants in the 50 kilowatt range should be ready for commercialization in the 1980's. The characteristics of these powerplants are high electrical efficiency and a cooling system that makes heat recovery possible. The potential for fuel cell powerplants covers a wide range of applications, from small units for motive power, through intermediate sizes for on-site residential/commercial or industrial cogeneration and utility peaking to large multimegawatt units for utility baseload generation. This report deals exclusively with fuel cell powered on-site integrated energy systems in a multifamily residential application.

Fuel cell powerplants have several features that are favorable for on-site applications including modularity, high electrical efficiency, and environmental acceptability in addition to the previously mentioned heat recovery potential. Modularity permits rapid installation of prepackaged units with a minimum of site preparation and a short lead time. Multiple units allow the system to meet reliability requirements without the need for excessive reserve capacity. High electrical efficiency combined with heat recovery result in a maximum total energy utilization in the 80 percent range for small powerplants in the range of 50 kW. Larger fuel cell powerplants have a potential energy utilization of as high as 95 percent (Ref. 1). Fuel cell gas emissions are well within current EPA requirements. With heat recovery the thermal discharge to the environment is small; and because of the static electrochemical nature of the process the fuel cell is very quiet. In general the fuel cell would be a good neighbor in a residential area.

The above considerations, as well as other studies (Refs. 2 and 3) indicate that fuel cells show an energy savings over conventional energy systems and other OS/IES powerplants. The purpose of this paper is to evaluate the effect of various fuel cell operating characteristics and the effect of coupling the powerplant with different building energy supply systems and components (e.g. a heat pump or absorption air conditioner). A breakeven cost comparison is preformed to determine the economic advantages, if any, of changing the fuel cell operating characteristics such as electrical efficiency and ratio of thermal/electrical energy produced.

BUILDING SITE

The application chosen for this study was an 81 unit garden apartment complex. The 81 unit module, composed of nine separate two story buildings, contains a mixture of 1 and 2 bedroom apartments with a total of 48 000 m^2 (520 000 ft^2) of conditioned area. The building size is of no particular consequence except that it is large enough to permit the use of high efficiency central air conditioning units. Since both the OS/IES and apartment complex are modular the results of this study are applicable over a wide range of sizes.

The individual buildings are of a current design and provide all conveniences and services commensurate with a modern facility. Each apartment is equipped with modern lighting, appliances and laundry facilities and is heated and cooled via forced air convectors. The data base for this application was developed by the Urban Systems Project Office of NASA's Johnson Space Center as part of a design done by NASA (Refs. 4 and 5) as a participant in the HUD-MIUS program. The Modular Integrated Utility System (MIUS) program was conducted by the Department of Housing and Urban Development (HUD) to develop and demonstrate the technical, economic, and institutional advantages of integrating the systems that provide all or part of the utility service for a community. The MIUS loads were calculated for a 324 unit multibuilding garden apartment complex; the 81 unit complex used here assumes only one fourth of the buildings with a corresponding reduction in energy requirements.

The identical apartment complex was sited in four geographic locations in the United States for the purpose of evaluating climate effects. Washington, D. C. represents the average climate for all seasons of the year. Minneapolis, Minnesota was selected to represent a severe winter and a mild summer while Houston, Texas represents the opposite, that is, a mild winter and a hot, humid summer. Las Vegas, Nevada is similar to Houston in terms of temperature but has a much dryer climate.

Table I gives the energy demand for the Washington location for three composite days. The data for each day represents the average demand for the Winter, Spring/Fall, or Summer season. Each day is broken into five segments; these segments are the basis for calculation. These data represent end-use demands that must be supplied by the utility system serving the apartment complex. The electrical demand is constant for the four locations, and is used to operate indoor and outdoor lighting, large and small appliances (including cooking), and motors for air handling. The energy required for domestic hot water is also constant for the four locations and is defined as the heat needed to raise potable cold water from its reservoir or well temperature to 60^{o} C (140^{o} F). Space heating and cooling demands represent the net heat loss or gain, from or to the apartment units, that is necessary to maintain the apartment temperature at 23^{o} C (74^{o} F) drybulb and 50 percent relative humidity.

Space conditioning demands for the cities other than Washington are obtained by the degree day method, that is, the space heating demand for

Houston is given by the heating demand of Washington multiplied by the ratio of heating degree days in Houston to heating degree days in Washington.

FUEL CELL PARAMETERS

The hypothetical fuel cells used in this study have a range of operating characteristics typical of those projected for first generation phosphoric acid fuel cells and state-of-the-art components (Ref. 1). In all cases natural gas was assumed to be the fuel and all efficiencies are based on the lower heating value of natural gas.

The powerplant produces electricity, on demand, for the normal electrical demands and other auxiliary demands such as heating and cooling as required. While producing electricity the powerplant also produces two grades of potentially useful heat. High grade heat is recovered from the cell stack coolant in the form of steam at a guage pressure of 1075 N/m^2 (15 psig) and a temperature of 121^o C (250^o F) which is then condensed and returned to the powerplant as 93^o C (200^o F) water. Low grade heat is recovered from stack exhaust gases in the form of hot water at 71^o C (160^o F).

Annual fuel consumption was calculated for a wide range of operating characteristics. Electrical efficiency, thermal efficiency, the ratio of high to low quality heat, and percent heat lost were varied. In an actual fuel cell these characteristics could be a result of varying operating temperature, operating pressure, catalyst loading, cell components, method of fuel processing, or heat recovery scheme to mention only a few.

Twenty fuel cells were paramaterized in this study. For presentation in this report four were selected as representative of options available to a fuel cell manufacturer. Specific operating characteristics for the four fuel cells are listed in Table II. Fuel cell B is the base powerplant and is a best guess of the actual operating characteristics of a first generation phosphoric acid fuel cell. Fuel cell A can be thought of as a high thermal efficiency version; it has the same electrical efficiency as B but recovers more heat and heat of a higher quality than B. Fuel cell C is the low thermal efficiency version, having the same electrical efficiency as fuel cell B but recovering less heat and heat of a lower quality than fuel cell B. Fuel cell D is the low electrical efficiency version, with the same amount of unrecoverable heat and same high to low quality heat ratio as fuel cell B.

ON-SITE ENERGY SUPPLY SYSTEMS

An on-site integrated energy system simultaneously supplies electrical and thermal energy to a user. Two fundamental design options are available. In one the system can be designed such that it exactly meets the electrical load and either generates heat by an auxiliary source to meet a heating requirement greater than can be satisfied by the powerplant or rejects heat to the environment if the energy system cannot use all the heat generated. In the other system design the powerplant generates all required heat and imports or exports electricity to a utility grid as necessary. A grid-connected system presents several problems. Most significant is that the shape of the demand curve for an on-site application will generally have the same shape as a utility's demand curve. The OS/IES will need to import electricity during a utility's peak demand and will have electricity to export during the utility's minimum demand period. Both of these tend to raise the utility's peak to base load ratio, something the utilities are actively trying to reduce. Also utility connection would put the OS/IES in the very gray area between a public utility and a privately owned energy supply system. This would open all sorts of tax, pricing, and ownership questions. For the above reasons it was decided to make the OS/IES grid independent for this study.

Grid independence requires an auxiliary heat source. In this study electricity is degraded to provide auxillary heat. This is reasonable from an energy standpoint since the total heat efficiency of a fuel cell (recoverable by-product heat plus the heat equivalent of the produced electricity) is in the same range as the efficiency of a fired boiler. Electricity degradation is also reasonable from a capital cost standpoint since for all but the coldest climates most of the additional powerplant capacity required is already installed to meet summer peak demand. Degrading electricity to heat makes the summer and winter peak electrical demands approximately the same, thus using the full design capacity of the power-plant a greater percent of the time.

The ground rules applied to each system were (1) the system must be completely independent, neither importing nor exporting electricity to a utility grid nor generating heat by direct combustion and (2) waste heat from the fuel cell must be used to the maximum practical extent. The second requirement is achieved by generating sufficient electricity to meet the basic electrical requirements. The heat produced as a by-product of electrical generation is used first for domestic hot water then, depending on the season, directly for space heating or indirectly via an absorption chiller for air conditioning. To satisfy any additional heating/cooling requirement additional electricity is generated (for resistance heating or to power heat pumps or compression chillers) only to the extent that by-product heat is fully used.

Within these ground rules eight promising systems were defined as described in Table III.

System 1 may be illustrated by Figure 1. The fuel cell powerplant supplies all A.C. power demands. Domestic hot water is supplied at 60° C (140° F) by heat exchange with the low quality heat source. Space heating and cooling demands are supplied via a two-pipe hot/chilled water circulation system. Hot water is provided from three potential sources. High and low quality fuel cell by-product heat are first used; any additional demand is satisfied by an electric boiler and the associated fuel cell by-product heat. Chilled water is supplied by two sources. Absorption chillers use the stack coolant stream, recover energy at a COP of 0.65 and return the condensate to the stack. Additional chilled water is supplied by large commercial compression chillers that work in conjunction with a cooling tower. Chilled water supply temperature is 7° C (45° F) with a return temperature of 13° C (55° F). Forced convection heat exchangers in each apartment add or remove heat as required.

System 2 differs from System 1 only in that the absorption chiller will accept feedwater as low as 88° C (190° F). These low temperature units have the same COP as the high temperature units but are necessarily larger to extract the same amount of heat from lower quality feedwater.

Systems 3 and 4 are analogous to Systems 1 and 2, respectively with the addition of hot water storage. Storage is used in the spring/fall season when no heating, but possible cooling is required during the day, and heating is required in the evening. Excess hot water available during the day is stored for use during the evening hours. The small cooling loads would require only one chiller. This would be a compression machine; the fuel cell by-product hot water would go to storage instead of feeding the absorption chiller. Hot water storage would require insulated tanks capable of storing 93° C (200° F) water. Powerplant operation would still be controlled by electrical demand, but use of by-product heat could be deferred until needed.

System 5 uses a central heat pump to supplement heating provided by fuel cell by-product heat. The heat pump also supplements cooling provided by high temperature absorption chillers. System 6 is like System 5 with the use of low temperature absorption chillers.

System 7, like System 5, uses a heat pump to supplement heating by fuel cell by-product heat. Unlike System 5 where the heat pump supplies all the make-up cooling, in System 7 only the capacity required for winter is installed; no additional capacity is added for the summer peak. Peak cooling capacity, above that which can be satisfied by heat pumps, is satisfied by more efficient compression chillers.

System 8 again satisfies heating demand with by-product heat and electric resistance heating. Cooling demand is satisfied, more conventionally, by individual compression air conditioners. These are less efficient than central units. And since they provide cooling directly there is no means of using by-product heat in absorption chillers.

Although Systems 2-8 are not illustrated, their layout can be visualized by making the changes described above to Figure 1. Component performance assumptions are listed in Table IV.

ANALYTICAL PROCEDURE

The basic for this energy analysis was load profiles computer for the MIUS Community Conceptual Design (Ref. 4). MIUS gives an hourly electrical demand that is assumed constant over the year and heating/

cooling load profiles for seasonal averages and summer and winter peaks. The seasonal average days were broken into five segments where the demand curve segment could be reasonably approximated by a constant demand. These data are given in Table I. Electrical demand was considered the same at each location. Heating/cooling demands were computed for the other three locations using degree day ratios provided by the U.S. Weather Bureau.

A computer program was written to do the actual fuel use computations. A brief description of the algorithm used explains the strategy for fuel usage calculations.

The fuel needed to generate the base electrical load is first calculated, and the amount of by-product heat produced is calculated and stored. Heat required for domestic hot water is next subtracted from the low quality heat pool. The remaining heat energy is then used to satisfy the space conditioning (heating and cooling) demand as allowed by each system. High quality heat can be used in all systems except System 8 in the cooling mode; low quality heat can be used only for heating and low temperature absorption chillers. After all the by-product heat from base load electrical generation is used most cases studied require additional space conditioning. This additional demand is satisfied by generating additional electricity only to the extent that the by-product heat produced is used to the maximum extent allowable by the particular building system.

Parametric calculations were performed for four locations, eight building systems, and twenty fuel cell variations. Only those combinations most representative of trends are reported in this paper.

DISCUSSION OF RESULTS

Energy Analysis

Results of the energy analysis for selected parametric cases are shown in Figures 2 to 5 and Table V. All values represent the annual fuel used to supply electric power, space conditioning, and domestic hot water to the full 81 unit apartment complex. Units are trillion joules and are based on the lower heating value of the fuel.

Figure 2 compares the annual fuel usage, which is a measure of the energy efficiency for each of the eight service supply systems. Throughout this discussion System 1 (electric resistance supplemental heat, high temperature absorption and supplemental compression air conditioning) coupled with fuel cell B will be refered to as the base OS/IES. For the Washington location this system uses 10.2×10^{12} J/yr (9.73×10^{9} Btu/yr). By going to a low source temperature absorption chiller a 4 percent fuel economy is realized. Systems 3 and 4 incorporate short term thermal storage into Systems 1 and 2, respectively. System 3 saves 2 percent of the fuel required by System 1. This savings is mostly from storing low quality heat during periods where cooling is required. Systems 5 and 6 incorporate a heat pump for supplemental heating in winter and supplemental cooling in summer. In order to incorporate a heat pump for both supplemental heating and supplemental cooling a system must sacrifice its very high efficiency compression chiller. This is not fuel conserving in most cases. System 5 requires 8 percent more fuel than base System 1. This can be explained by looking at the relative efficiencies of the three supplemental space conditioning devices. The heat pump COP is larger than the electric resistance COP that it replaces for supplemental heating (i.e., smaller power requirement for the same heat production); but for supplemental cooling the heat pump COP is much smaller than the compression chiller COP that it replaces (i.e., larger power requirement for the same account of cooling). For the Washington area the relative supplemental cooling/supplemental heating demands (along with ambient conditions that affect heat pump performance) are such that the increased summer power requirements outweigh the decreased winter power requirements. This situation is reversed in colder climates.

The situation also changes somewhat in System 6 where low temperature absorption chillers are used. The low temperature chillers satisfy a higher percentage of the cooling load thus reducing the supplemental cooling/supplemental heating demand ratio to a point where Systems 2 and

6 have approximately the same fuel requirement. In Systems 5 and 6 the comparison between low and high temperature absorption chillers point out two results. First this is the strongest case for inclusion of low temperature absorption chillers and second, but perhaps more significant, this shows the need to evaluate different system combinations in light of location. The building industry cannot zero in on one particular OS/IES design and expect it to be the most energy efficient in all locations and applications.

System 7, with heat pumps, compression and high temperature absorption chillers saves some (1.4 percent) fuel when compared to System 6 but the added complexity would probably outweigh any fuel savings.

System 8 results in the greatest amount of fuel usage, 23 percent more than System 1, and is an indication of the savings that are possible using recoverable powerplant heat.

The Washington climate is temperate; any harsher climate should magnify the results of the energy analysis of the Washington area. The climatic effect is shown for selected systems in Figure 3. Systems 1 and 2 in general show a smaller climatic effect than Systems 5 and 8. This is because Systems 1 and 2, in general, have a higher overall efficiency than Systems 5 and 8. The only exception is System 5 in Minneapolis where the supplemental heating gains outweigh the supplemental cooling loss as previously discussed. Houston and Las Vegas show greater benefits from storage since they have greater demands for both heating and cooling in the same day. The high fuel demands for Houston and Las Vegas in Systems 5 and 8 are due to the lower air conditioning COP with the large air conditioning loads. To a lesser extent System 8 in Minneapolis and Washington is also affected by the low air conditioning COP. The increase in fuel consumption is not so large as in Houston and Las Vegas because the air conditioning load is small.

Figure 4 compares the four fuel cells (described in the Fuel Cell Parameters section) for Systems 1 and 2 in the Washington location. Fuel cell B is the best guess of actual first generation phosphoric acid fuel cell performance, and will be used as the basis for most comparisons. Comparing fuel cells A and B for System 1 shows that gaining five points in heat recovery in fuel cell A yields a four percent reduction in fuel consumption, while losing five points in electrical efficiency in fuel cell D results in a seven percent increase in fuel consumption due to the high COP of electrically driven devices. The fuel cell thermal/electric ratio is a good indicator of the utility of an absorption chiller that can use a low temperature (110° C) source as can be seen by the unshaded portion of each of the bars in Figure 4. The fuel cell with the highest thermal/electric ratio (i.e. D) shows the most effect of low temperature chillers.

Figure 5 shows that location has some effect on the fuel cells and systems presented in Figure 4 but the effect is not as large as the effect of system choice (Fig. 3). The only trend is that Houston and Las Vegas, with their high air conditioning demand, are more sensitive to electrical efficiency while Minneapolis with the high heating demand is more sensitive to heat efficiency.

Table V gives the yearly fuel usage for all four cities, all four fuel cells and for Systems 1, 2, 5, and 8. In only two cases was usable heat rejected to the environment; these are indicated in the table by an asterisk.

Economic Analysis

The second part of this study was an economic analysis in which the breakeven cost of selected fuel cell powerplants was calculated. The breakeven cost was based on the fuel savings of a powerplant/system combination compared to fuel cell B in the same system. If fuel usage was the only consideration the fuel cell with the highest electrical efficiency coupled with maximum heat recovery would be the powerplant chosen. In general, though, any increase in electrical efficiency or heat recovery efficiency is accompanied by an increase in capital cost. The manufacturer of OS/IES equipment must strike a balance between the lower first cost of a lower efficiency machine and the yearly fuel savings of a more efficient, though higher first cost machine.

Figure 6 shows the incremental capital cost allowed by fuel savings. Fuel cells A, C, and D are compared to fuel cell B for System 1 in the Washington location only. Washington was selected because of its temperate climate and because the original MIUS data is for Washington the fuel consumption for that location is the most accurate; System 1 represents a typical OS/IES application. No assumptions were made concerning the cost of powerplant B; all that is shown is the maximum additional cost of the more efficient fuel cell system A and the minimum cost reduction for the less efficient fuel cell systems C and D. For example, at a fuel price of $\$38/10^9$ joules at most a \$50/kW premium can be paid for fuel cell A. This is about 10 percent of the powerplant cost according to recent price projections that range from \$400/kW (Ref. 6) to \$625/kW (Ref. 7).

CONCLUSIONS

The 81 unit garden apartment used in this study is believed to be typical of those constructed in the mid 1970's so the conclusions (trends not actual fuel consumption) can be generalized to any typical multifamily residential complex. The OS/IES system component choices are a major factor in annual fuel consumption; the least efficient system using up to 25 percent more fuel than the most efficient. Central air conditioning, thermal storage, and heat pumps lead to minimum fuel consumption while individual compression air conditioning units (which tend to break with the integrated energy concept) lead to the highest fuel consumption. The projected range of fuel cell operating characteristics has less of an effect (up to 12 percent) on fuel consumption than system component choices. In general the fuel cell with the highest electrical efficiency has the lowest fuel consumption; this is most apparent in applications with a low thermal/electric ratio such as an area with a high air conditioning demand. Though location has a substantial effect on fuel consumption, location does not significantly alter the trends that are the basis of the general conclusions. The fuel cell trends are especially independent of location.

Differences in fuel consumption have a significant influence on allowable powerplant costs. Due to fuel cost alone, the most efficient fuel cell (powerplant A) can absorb a \$50/kW premium at a $\$3.8/10^9$ joules ($\$4/10^6$ Btu fuel price).

Finally, the wide variation in fuel consumption with fuel cell characteristics, balance-of-plant equipment, and location indicates that one system design is insufficient to insure fuel conservation in all locations. If different OS/IES applications are considered it becomes more apparent that unique fuel cell/balance-of-plant designs are needed for each application.

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TABLE I. - ENERGY DEMANDS, WASHINGTON AREA

	Noon-6 pm	6 pm-Midnight	Midnight-6 am	6 am-10 am	10 am-Noon
Space heating (negative indicates cooling required)					
Winter	3.20×10^6 Btu/ 3.37×10^9 J	3.65/3.85	7.00/7.38	4.35/4.58	1.70/1.79
Spring/Fall	-3.25/-3.42	-1.75/-1.84	2.95/-3.11	0.90/0.95	-0.35/-0.37
Summer	-9.85/-10.38	-8.35/-8.00	-1.45/-1.53	-3.25/-3.42	-2.60/-2.74
Electricty all seasons	1.38/1.45	2.64/2.78	1.09/1.15	0.96/1.01	0.44/0.46
Domestic hot water all seasons	0.47/0.49	0.90/0.95	0.37/0.40	0.32/0.34	0.15/0.16

TABLE II. - FUEL CELL

PERFORMANCE ASSUMPTIONS

[Natural gas as fuel.]

Fuel cell A high heat efficiency	40% electricity 35% 160° F water 15% 250° F steam 10% loss
Fuel cell B base case	40% electricity 36% 160° F water 9% 250° F steam 15% loss
Fuel cell C low heat efficiency	40% electricity 31% 160° F water 4% 250° F steam 25% loss
Fuel cell D low electrical efficiency	35% electricity 40% 160° F water 10% 250° F steam 15% loss

TABLE III. - ON-SITE INTEGRATED ENERGY SYSTEMS

System	
1	Heating - by-product heat and electric resistance Cooling - central compression A/C and high temperature absorption A/C 110° C (230° F source)
2	Same as System 1 with low temperature absorption A/C
3	Heating - by-product heat, electric resistance and stored heat from cooling cycle Cooling - central compression A/C and high temperature absorption A/C, excess heat to storage
4	Same as System 3 with low temperature absorption A/C
5	Heating - by-product heat and central heat pump Cooling - central heat pump and high temperature absorption A/C
6	Same as System 5 with low temperature absorption A/C
7	Heating - by-product heat and central heat pump Cooling - central heat pump (capacity determined by heat load), high temperature absorption A/C and compression A/C
8	Heating - by-product heat and electrical resistance Cooling - individual compression A/C

TABLE IV. - SYSTEM COMPONENT

PERFORMANCE ASSUMPTIONS

Centralized compression chiller	4.5 COP
Individual compression chiller	2.1 COP
Absorption chiller	0.65 COP
Heat pump	1.5-2.8 COP
Electric resistance heat	95% percent
Storage	100% percent

TABLE V. - ANNUAL FUEL USAGE; SELECTED SYSTEMS

City	Fuel cell	System number			
		1	2	5	8
Washington	A	9.37×10^{9} Btu/ 9.88×10^{12} J	8.98/9.46	10.12/10.67	11.74/12.37
	B	9.73×10.26	9.30/9.80	10.51/11.08	12.00/12.65
	C	10.46/11.02	[a]10.23/10.78	11.06/11.66	12.62/13.30
	D	10.44/11.00	9.80/10.33	11.56/12.18	13.08/13.79
Houston	A	10.94/11.53	10.20/10.75	15.61/16.45	17.08/18.00
	B	11.17/11.77	10.40/10.96	16.23/17.11	17.16/18.09
	C	11.56/12.18	[a]11.18/11.78	16.90/17.81	17.38/18.32
	D	12.49/13.16	11.38/11.99	18.17/19.15	19.42/20.47
Minneapolis	A	11.02/11.62	10.70/11.28	10.53/11.10	12.19/12.85
	B	11.49/12.11	11.17/11.77	10.92/11.51	12.61/13.29
	C	12.57/13.25	12.38/13.05	11.69/12.32	13.60/14.33
	D	12.05/12.70	11.54/12.16	11.77/12.40	13.35/14.07
Las Vegas	A	11.54/12.16	10.81/11.39	14.24/15.01	17.73/18.69
	B	11.88/12.52	11.11/11.71	14.74/15.51	17.90/18.87
	C	12.48/13.15	12.11/12.76	15.36/16.19	18.34/19.33
	D	13.05/13.75	11.93/12.57	16.40/17.28	20.01/21.09

[a]Indicates by-product heat that must be rejected from systems that are capable of using all by-product heat.

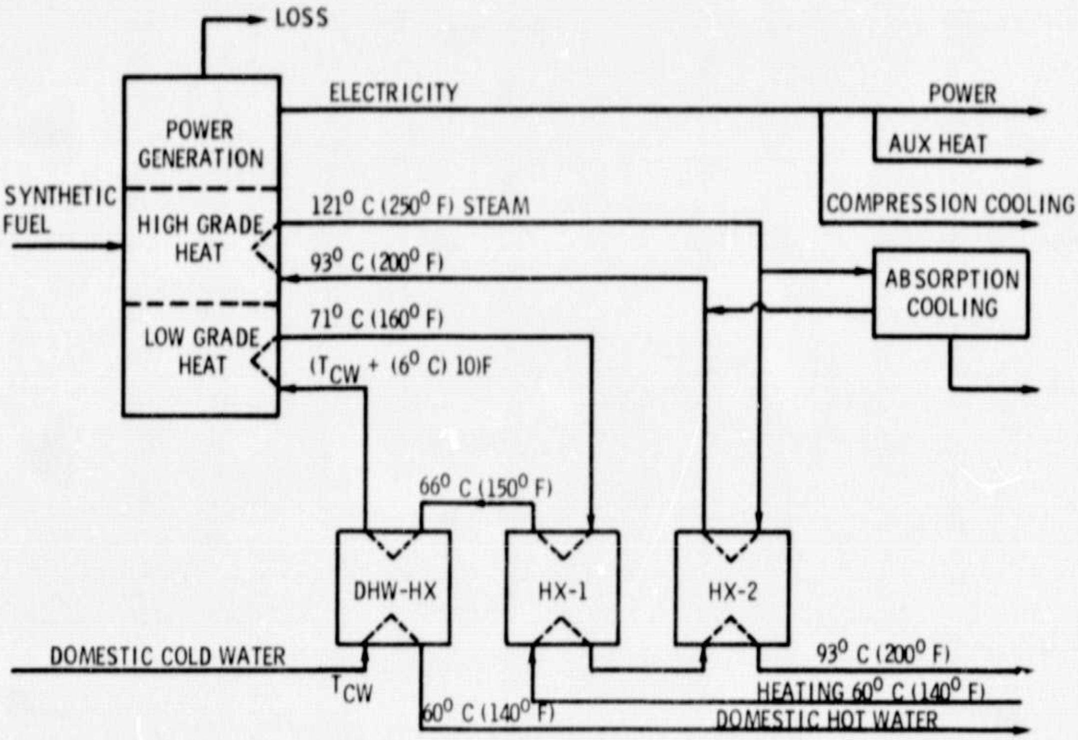

Figure 1. - On-site integrated energy system 1.

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SYSTEM	SYSTEM NUMBER
1	HEATING - BY-PRODUCT HEAT AND ELECTRIC RESISTANCE COOLING - CENTRAL COMPRESSION A/C AND HIGH TEMPERATURE ABSORPTION A/C 110° C (230° F SOURCE)
2	SAME AS SYSTEM 1 WITH LOW TEMPERATURE ABSORPTION A/C
3	HEATING - BY-PRODUCT HEAT, ELECTRIC RESISTANCE AND STORED HEAT FROM COOLING CYCLE COOLING - CENTRAL COMPRESSION A/C AND HIGH TEMPERATURE ABSORPTION A/C, EXCESS HEAT TO STORAGE
4	SAME AS SYSTEM 3 WITH LOW TEMPERATURE ABSORPTION A/C
5	HEATING - BY-PRODUCT HEAT AND CENTRAL HEAT PUMP COOLING - CENTRAL HEAT PUMP AND HIGH TEMPERATURE ABSORPTION A/C
6	SAME AS SYSTEM 5 WITH LOW TEMPERATURE ABSORPTION A/C
7	HEATING - BY-PRODUCT HEAT AND HEAT PUMP COOLING - CENTRAL HEAT PUMP (CAPACITY DETERMINED BY HEAT LOAD), HIGH TEMPERATURE ABSORPTION A/C AND COMPRESSION A/C
8	HEATING - BY-PRODUCT HEAT AND ELECTRICAL RESISTANCE COOLING - INDIVIDUAL COMPRESSION A/C

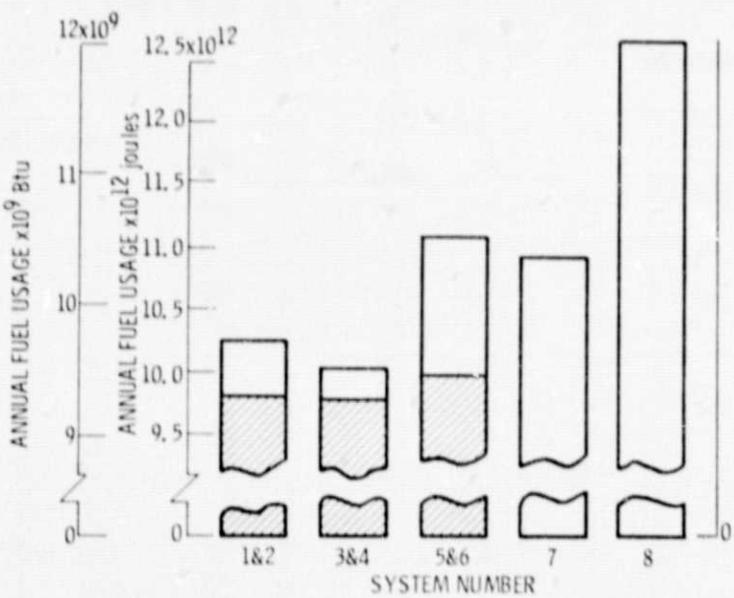

Figure 2. - Fuel usage dependence on system. Washington location and powerplant B.

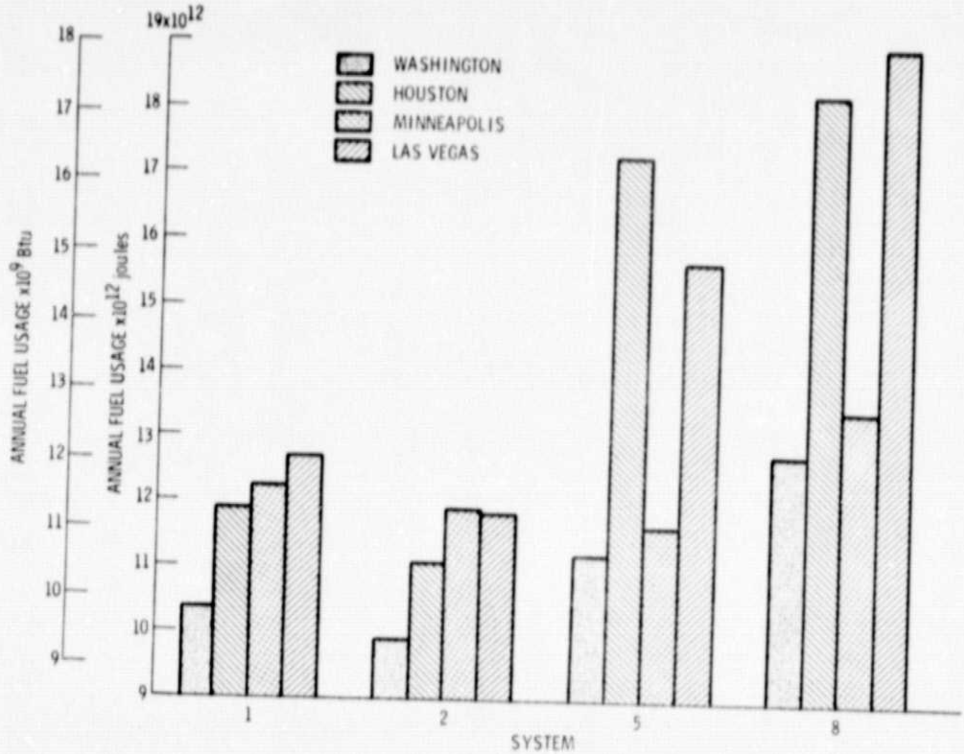

Figure 3. - Fuel usage dependence on location and system. Powerplant B.

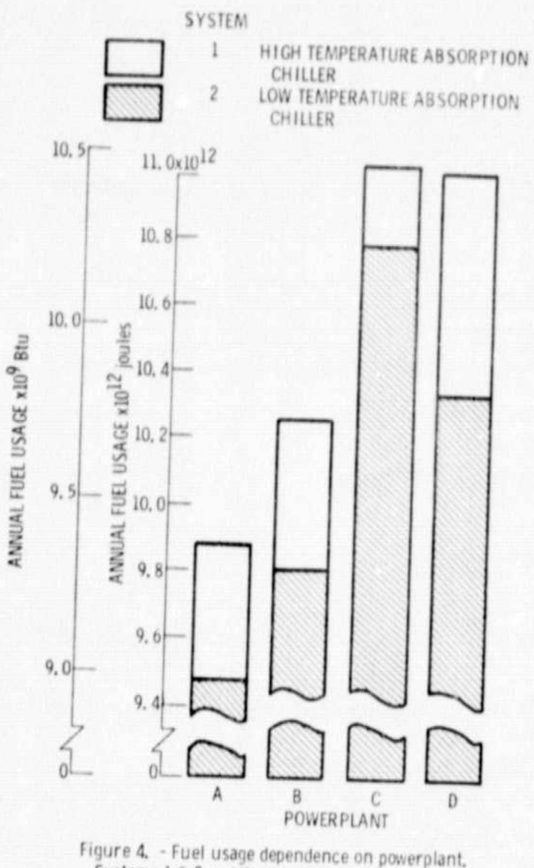

Figure 4. - Fuel usage dependence on powerplant. Systems 1 & 2 and Washington location.

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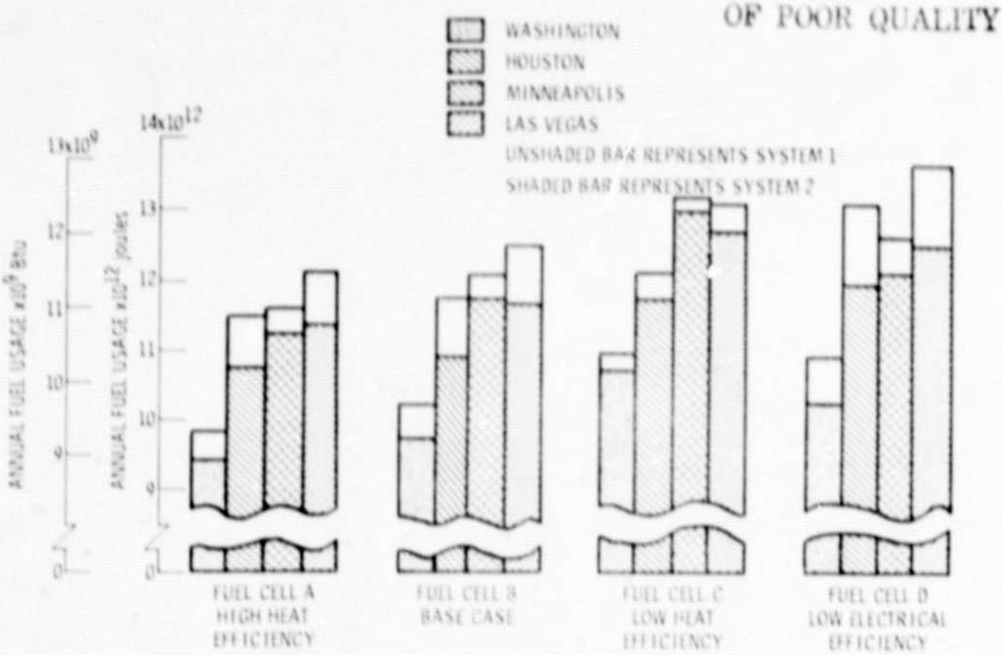

Figure 5. - Fuel usage dependence on powerplant and location. Systems 1 and 2.

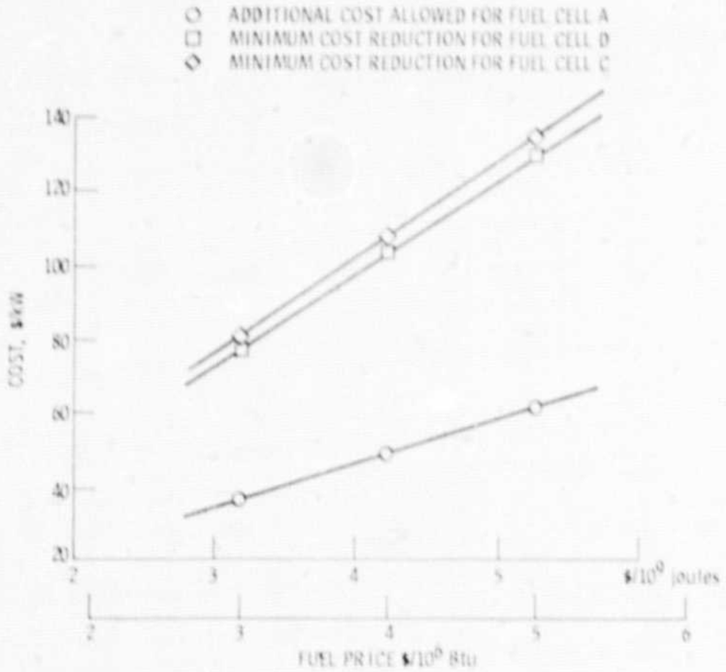

Figure 6. - Incremental breakeven cost, relative to fuel cell B. Washington location; system 1; and 13 percent fixed charge rate.