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THE POTENTIAL BENEFIT OF AN ADVANCED
INTEGRATED UTILITY SYSTEM

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AN ADVANCED INTEGRATED UTILITY SYSTEM (NASA)
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16. Abstract The applicability of an advanced integrated utility system based on 1980 technology is investigated. An example of such a system, which provides electricity, heating and air-conditioning, solid waste disposal, and water treatment in a single integrated plant, is illustrated for a hypothetical apartment complex. The system requires approximately 50 percent of the energy and approximately 55 percent of the water that would be required by a typical current conventional system.			
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THE POTENTIAL BENEFIT OF AN ADVANCED
INTEGRATED UTILITY SYSTEM

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SUMMARY

An investigation was made of the potential benefit of an advanced integrated utility system, which provides the services of electrical power, heating and air-conditioning, solid waste disposal, and water treatment in a single integrated plant. The system investigated incorporates technology assumed to be available in 1980 (with some development work) to serve a hypothetical apartment complex.

The investigation centers around an example of a possible integrated system. The example chosen features a pyrolytic process for disposal of solid waste, closed-Brayton-cycle engines and fuel cells, solar collection, and absorption and compression chillers. The system treats wastewater using a process that also simultaneously removes sulfur dioxide and oxides of nitrogen from exhaust gases.

The system uses approximately 45 to 60 percent less energy than a current conventional system (depending on concurrent implementation of architectural energy-saving techniques in the apartment complex) and approximately 45 percent less water. The system is capable of using several fossil or synthetic fuels. The savings and multifuel capability clearly indicate the potential benefits of the advanced integrated utility concept in conserving fuel and water resources.

INTRODUCTION

Since the summer of 1972, the Urban Systems Project Office (USPO) at the NASA Lyndon B. Johnson Space Center (JSC) has been studying conceptual and preliminary designs of alternate ways of providing utility services. The bulk of this work has been carried out under the auspices of a Department of Housing and Urban Development (HUD) project called the modular integrated utility system (MIUS). The

purpose of this project is to design and demonstrate technical, economic, and institutional aspects of an onsite utility system that integrates the functions of electrical power generation, heating and air-conditioning, solid waste disposal, and water processing. The purpose of integrating these functions is to optimize the performance of a total utility system by recovering energy from power generation processes and from solid waste disposal for use in space heating, air-conditioning, and water heating, and by reusing treated wastewater for purposes other than human consumption. These techniques are intended to conserve natural resources such as fossil fuels and water, to simultaneously minimize the impact on the environment, and to require a cost compatible with that of conventional systems.

The HUD MIUS program is intended to induce implementation of the concept by private or public utility service organizations through initial HUD-sponsored development and demonstration. The MIUS concept is an extension of the total energy concept initiated in the 1960's for onsite power generation and recovery of otherwise wasted heat to provide heating and absorption air-conditioning. Many such plants are now in operation in the United States at various facilities such as office buildings and apartment complexes.

The USPO completed a series of conceptual designs of MIUS systems for various types of facilities, including garden apartments, an office building, a shopping center, a hospital, a school, and a high-rise apartment. Subsequently, the application of the MIUS to a new community of 100 000 people was studied. The new town of Columbia, Maryland, was used as a model. Considerable attention was given to how the phased development of the town over a 20-year period affected the optimum technique for incrementally adding utility capacities. As a result of these studies, the characteristics of a baseline MIUS system were derived. The conclusion was drawn that, compared with a conventional utility system, approximately 20 to 35 percent energy could be saved depending on the circumstances of the application.

During the conduct of these technical studies, a market study was performed to determine the availability of potential MIUS applications. It was concluded that an apartment complex of approximately 300 to 1000 dwelling units would have a good market potential for MIUS applicability. A more detailed design of an MIUS system was then conceived for a 496- and a 992-unit apartment complex. This work resulted in a preliminary baseline design of an MIUS system.

In addition to conducting technical studies, NASA has also designed and implemented a small-scale version of an MIUS system called the MIUS Integration and Subsystems Test facility located at JSC. This system operates on simulated electrical, heating, and air-conditioning loads and is used to treat wastewater and to incinerate solid waste. The testing program was begun in the spring of 1974 and has included a wide variety of tests to understand and verify potential MIUS processes.

The baseline MIUS design work was conducted under a ground rule imposed by HUD that restricted the MIUS components to currently available state-of-the-art equipment called "articles of commerce." This restriction was intended to facilitate an early demonstration of the MIUS concept. However, it is believed that, with some development work, a more efficient and flexible integrated utility system would be feasible in a few years by removing the articles-of-commerce constraint. To this end, a study was made to assess the potential of an advanced integrated utility system (IUS) that applies new technology. The results of that study are presented in this paper.

Many approaches, potential processes, and equipment existing or under development could have been applied to this study. However, the primary purpose was to investigate the potential of the advanced IUS concept to determine its worth for further consideration. Therefore, one possible conceptual design was developed for analysis as an example of an advanced IUS without any attempt to perform a detailed investigation to determine the most optimized design.

A summary review of the work done on the baseline MIUS design is the first section in this paper. The example of an advanced IUS is then discussed, including the ground rules used in the design approach, a description of the various utility services and their integration, some techniques for conserving energy through architectural design, and an analysis of energy and water usage compared to usage in conventional utility systems and in the baseline MIUS design.

Three appendixes are included. Appendix A is a description of a technique developed in the MIUS design work for storing thermal energy, appendix B is a discussion of the uses of various fossil and synthetic fuels in power generation options, and appendix C is a list of candidate architectural energy-conserving techniques.

The study documented in this paper was accomplished by engineers in the JSC Urban Systems Project Office with the author's coordination and integration. Various topics in

the paper are principally the work of the following people: solid waste disposal, Richard C. Wadle; electrical power generation, Vernon Shields and Tony E. Redding; heating, ventilation, and air-conditioning, James O. Rippey; water treatment, Harmon L. Roberts; architectural energy-saving techniques and appendix C, architects Emmett White and Ray Wobbe of Clovis Heimsath Associates, Inc.; and consumables analysis, Steven P. Wallin. Acknowledgment is also made to Alan E. Brandli for comprehensive review and helpful comments on the original study documentation and to James O. Rippey and Tony E. Redding for providing appendixes A and B, respectively.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Systeme International d'Unites (SI). The SI units are written first, and the original units are written parenthetically thereafter.

BASELINE MIUS DESIGN

As indicated in the Introduction, the most detailed MIUS design rendered was for 496- and 992-dwelling-unit apartment complexes. The design is summarized in this section.

The model for the apartment complexes was conceived by a team of architects under contract to NASA. This team made surveys in different sections of the United States and developed a representative model. The site plan for the 496-unit complex is shown in figure 1. Figure 2 is an architectural rendering showing the MIUS plant in relation to part of the apartment complex. The 45 000-square-meter (11.2 acre) site has a 10-story high-rise building and 19 three-story garden apartment buildings of three different types. To obtain the 992-unit complex, the site plan was simply doubled.

Because of the effects of weather on heating and air-conditioning demands, the model was located in a median climate for the continental United States. Washington, D.C., was chosen as representative of a median climate. A computer analysis was performed by using Washington, D.C., weather data and by modeling the structure, characteristics, and typical utility usages of the site buildings; utility loads were derived for electrical power, heating, air-conditioning, solid waste, and water; and an integrated system was designed.

An overview of this baseline MIUS system is illustrated in figure 3. The design includes diesel engines for generating electricity and incinerators for disposal of

solid waste. Heat produced in these processes is converted into steam as a byproduct, which is used in three ways: (1) the steam is used to heat a hot water loop preheated by some lower grade heat recovered from the engines and thereby provides for domestic water and space heating; (2) the steam is used in absorption air-conditioning, which is supplemented by compression air-conditioning to provide chilled water for space cooling; and (3) the unused heat contained in the steam is rejected to a cooling tower, which also provides heat rejection for the operation of the chillers and the hot water loop as required. A water tank is provided wherein either chilled or heated water for space conditioning can be temporarily stored. The principal effect of this type of storage is that it allows reduction of the peak electrical load required for compression cooling and thus reduces the required installed electrical generating capacity. (See appendix A for a discussion of the thermal storage technique used.)

In the baseline MIUS system, potable water is treated by conventional means and sewage is treated by using a biological system supplemented by a tertiary physical/chemical system. Sludge is transferred to the incinerator for disposal. The treated wastewater is stored in a holding tank and is used primarily for cooling-tower heat rejection and blowdown; it is also used for makeup and blowdown for other MIUS processes and for fire protection and irrigation of the apartment complex.

A comparison was made between the energy and consumables usages of the MIUS and those of a typical conventional utility system. These results are summarized in figure 4 for the 496-unit complex. The 992-unit complex showed a slight increase in energy savings from 30 to 32 percent. Also, cost comparisons with a conventional system were made; the results showed that the costs of providing the utilities would be relatively comparable over a 20-year period. Again, the 992-unit complex compared slightly more favorably.

In addition to the size variations, the effects on the MIUS system from climatic variations were evaluated. The 496-unit complex was studied using weather data from Minneapolis to represent a cold climate, from Houston to represent a hot and wet climate, and from Las Vegas to represent a hot and dry climate. No outstandingly significant changes were required in the MIUS system to accommodate these locations. The amount of energy saved when compared to a conventional system increased slightly with latitude because of the more effective use of recovered heat in the winter. However, between Houston and Minneapolis, the energy-saving increase was less than 2

percent. Some cost differences resulted from local cost indexes.

ADVANCED INTEGRATED UTILITY SYSTEM DESIGN

To facilitate comparisons with the baseline MIUS design, the 992-unit apartment complex was used as a model for the advanced IUS design together with the Washington, D.C., weather data as a representative median climate for the continental United States. The advanced system provides the same services as those provided by the baseline MIUS system: electrical power, space heating and cooling, solid waste disposal, potable water (including domestic water heating), and wastewater treatment. However, the systems design is based on technology that would be available by approximately 1980 after a reasonable amount of development work.

In the following sections, some general ground rules that are considered reasonable constraints to the integrated utility services are listed first. Next, an example of an advanced system for the 992-unit complex is described together with an approach to the design of such a system. A detailed discussion of each utility service and its interfaces then is presented. In providing a comparison to previous work, no attempt has been made to alter the apartment model from that used in the baseline MIUS. However, following the discussions of the utility services, techniques are presented for making architectural changes to the apartment complex model for conserving energy. Finally, energy and water use in the advanced design are analyzed and compared to usage in the baseline MIUS and in a conventional system.

Ground Rules

The following are general ground rules for each of the utility services. They are intended to provide reasonable bounds consistent with designing an integrated system capable of being implemented in 1980.

Electrical power generation.- The electrical system will be operationally independent of any existing grid but capable of being serviced by a grid for contingencies. Its reliability will be comparable to a conventional system. Oil and natural or synthetic gas will be assumed to be available. Emphasis will be on multifuel capability (i.e., a system capable of operating on more than one fuel). Heat recovery equipment will be used and will be compatible with the heating and air-conditioning services. Emissions will be consistent with applicable environmental guidelines.

Heating and cooling.- Maximum use of heat recovered from other utility processes will be made for space heating, air-conditioning, and water heating. Treated wastewater will be used to provide heat rejection to the environment required by the utility processes.

Solid waste disposal.- Solid waste from the apartment complex will be processed onsite. Although it would result in saving fossil fuel energy, importing additional solid waste from surrounding areas will not be considered. Unusable products from solid waste treatment processes will be deposited in a remote landfill. Emissions and effluents will be consistent with applicable environmental guidelines.

Water treatment.- Potable-water treatment will comply with the 1962 U.S. Public Health Service standards for drinking water. Low-water-consumption devices for toilets and showers will be used. (These devices, recently developed by industry, save approximately 30 percent water for toilets and 90 percent water for showers.) Wastewater will be treated to a quality consistent with reuse for all functions except human consumption. Adequate water pressure and storage for firefighting will be provided. Wastewater effluent will be consistent with applicable environmental guidelines. A storm water system will be considered available for effluent disposal.

System Overview and Design Approach

The system studied and presented here is an example of a possible advanced IUS and was investigated to assess potential performance. New techniques potentially amenable to an integrated system for providing each utility service were identified, and one possible combination that appeared to be promising was suitably integrated into an advanced system. The system chosen is illustrated in figure 5. A brief description of the system and the design approach used are presented in the following paragraphs. The individual utility services, or subsystems, are discussed in more detail in subsequent sections.

Because the apartment complex model was unchanged, the advanced system must provide the same utility loads required for the baseline MIUS design. To convey the approximate size of the system, some key design loads are presented as follows: peak domestic electrical load (not including that required by the utility system), 1688 kilowatts; peak heating load, 3.4 megawatts (11.8×10^6 Btu/hr); peak cooling load, 3810 kilowatts (1084 tons); solid waste load, 5443 kg/day (12 000 lbm/day); peak potable water load, 840 m³/day (222 000 gal/day); and peak wastewater load, 893 m³/day (236 000 gal/day).

The advanced system design includes a pyrolytic process for disposal of solid waste. The fuel produced by the pyrolysis is used in fuel cells to produce electricity. The remainder of the electrical power required is produced by high-efficiency closed-Brayton-cycle gas turbines. Heat is recovered from the fuel cells and from the Brayton cycle engines and supplemented by heat produced by solar collectors on apartment building roofs. This heat is then used in the same three ways as the heat recovered in the baseline MIUS design. These methods are reiterated as follows: (1) the recovered heat is used to provide domestic water and space heating; (2) the heat is used in absorption air-conditioning, which is supplemented by compression air-conditioning; and (3) any unused heat is rejected to a cooling tower, which also provides heat rejection for the chillers. Also, as in the baseline MIUS system, a water tank is provided wherein either chilled or heated water can be temporarily stored. Again, the principal effect of this type of storage is that it allows reduction of the peak electrical load required for compression cooling, and thus reduces the required installed electrical generating capacity. (Appendix A provides a detailed description of the thermal storage technique.)

In the advanced system, potable water is treated by conventional means depending on the untreated water source. Sewage is treated by a physical/chemical system that simultaneously aids in improving environmental quality by scrubbing the sulfur dioxide and oxides of nitrogen from the plant stack gases while using sulfur dioxide as a part of the wastewater treatment process. The system provides tertiary quality water. Dried sludge is transferred to the pyrolysis unit for disposal. Similar to the baseline MIUS system, a portion of the treated wastewater is stored in a holding tank and reused for cooling-tower heat rejection and blowdown, for makeup and blowdown in other MIUS processes, for fire protection, and for irrigation of the apartment complex grounds.

The general approach used in designing the advanced system is as follows. The amount of solid waste available for pyrolytic processing was determined, and, from this figure, the amount of fuel available for fuel cell electrical power generation was calculated. The fuel cells were then sized accordingly, and the amount of electricity they could provide was subtracted from the total required. This figure represented the capacity of the Brayton cycle engines. The amounts and temperatures of recoverable heat from both power generation processes were determined. Then, the amount and temperature of heat available from solar collectors on the roofs of all the buildings in the complex were determined and added to the amount of heat recoverable from power generation. The heat required for domestic water

heating, space heating, and cooling by absorption was determined for the winter and summer peak conditions and for the average conditions of the four annual seasons. Recoverable heat was insufficient to use only absorption air-conditioning to satisfy the cooling demands of the peak and average summer conditions. Consequently, the required compression cooling capacity was determined, and the amount of additional electricity required from the Brayton cycle was calculated. The use of thermal storage, however, negated any requirement to increase the installed power generation capacity.

The advanced IUS water system was designed with a considerably lower capacity than that required for conventional systems because of the use of low-water-consumption showers and toilets. The wastewater treatment effluent was reduced further by its reuse in the MIUS processes and for irrigation. The amount of sulfur dioxide required by the particular wastewater treatment process chosen was reduced by the amount available from the stack gases. Disposal of sludge was in the pyrolysis unit, thereby affecting the size of that unit.

Solid Waste Disposal

Disposal of solid waste is accomplished by pyrolysis. Pyrolysis is a destructive distillation process that is conducted at high temperature (approximately 1033 K (1400° F)) in the absence of oxygen and that produces gases usable as fuel.

The solid waste produced by the apartment complex is assumed to be 2.3 kg/day (5 lbm/day) for each person, making a total of approximately 5443 kg/day (12 000 lbm/day). Its heating value is assumed to be 11 622 kJ/kg (5000 Btu/lbm) with a density of 160 kg/m³ (10 lbm/ft³). The pyrolysis unit is also used to dispose of the sludge produced by the wastewater treatment process. The amount of sludge produced daily is 726 kilograms (1600 pounds mass) at 85-percent solids. Its heating value is assumed to be 2324 kJ/kg (1000 Btu/lbm) of dry solids. The heating value is low because of the high noncombustible chemical content of the sludge. The gas produced by pyrolytic disposal of the sludge is assumed to be insignificant.

The amount of energy in the 5443 kg/day (12 000 lbm/day) of solid waste at 11 622 kJ/kg (5000 Btu/lbm) is 732 kilowatts (60 X 10⁶ Btu/day). Based on current development work by industry, at least 60 percent of the energy in the solid waste (approximately 439 kilowatts (36 X 10⁶ Btu/day)) can be recovered from the pyrolytic process in the form of gas. The components of the gas and their volumes and

heating values are shown in table I. The total gas produced has a heating value of approximately $16\,755\text{ kJ/m}^3$ (450 Btu/ft^3). In the integrated system described here, the gas is used in hydrogen-oxygen fuel cells to produce electrical power. This process requires that the hydrogen in the various gas components be reformed as described in the next section.

Electrical Power Generation

Electrical power is generated using a combination of fuel cells and closed-Brayton-cycle processes. Both are currently under development by industry, and both have energy conversion efficiencies of approximately 40 percent. A simplified functional block diagram of the power generation subsystem is illustrated in figure 6. The peak electrical load, including the apartment complex and an estimate of the power requirements of the utility plant, is approximately 2050 kilowatts; the annual average load is approximately 1200 kilowatts.

The gases available from the pyrolysis process are sufficient to operate a 175-kilowatt fuel cell. However, the hydrogen must be removed from the various gases with a reformer. (A reformer process uses steam and a catalyst to change one hydrocarbon compound to another; in this case, it would be used specifically to remove hydrogen from hydrocarbon compounds. The reformer process is considered in the overall 40-percent efficiency of the fuel cell.) The fuel cell produces direct current, which is converted to alternating current with an inverter. Heat from the fuel cell operation is recoverable from two sources: (1) hot water at a temperature of approximately 339 K (150° F) from the exhausts of the cell stacks and from the reformer, and (2) low-pressure steam at a temperature of approximately 436 K (325° F) from the cell-stack coolant loop.

The smallest Brayton cycle prime movers for which design and estimated performance data are currently available are rated at 1200 kilowatts. Consequently, to satisfy the peak load of 2050 kilowatts, two 1200-kilowatt prime mover/generators are required. A third and possibly a fourth prime mover/generator would be used for standby redundancy; that is, for contingency or planned outages. Because the closed Brayton cycle uses external combustion, it can operate on any of several fuels, such as oil or natural or synthetic gas (including pyrolysis gas) or it can even use pulverized coal. (See appendix B for a discussion on fuels.) Heat can be recovered in a temperature range from 294 to 436 K (70° to 325° F), as desired, by using a heat exchanger between the recuperator and the compressor.

The fuel cell will provide approximately 15 percent of the annual electrical demand. However, in this particular system, because two Brayton cycle engines can provide 225 kilowatts more power than the peak demand, a fuel cell is not needed. The pyrolysis gases can be used in the Brayton cycle with approximately the same conversion efficiency. Nevertheless, there are applications for which additional solid waste can be imported, or the power profiles might be such that the fuel cell would be a more appropriate power generator (e.g., to supply peak loads or to reduce installed capacity of rotating machinery).

Heating, Ventilation, and Air-Conditioning

The heating, ventilation, and air-conditioning (HVAC) system manages available energy in the form of recovered heat from the Brayton cycle engines, the fuel cell, and the solar collectors to supply energy required for space heating, space cooling, and domestic water heating. The daily space heating and cooling loads vary with the weather, whereas the domestic hot water load is constant throughout the year. The HVAC loads were derived by computer analysis considering environmental conditions, building construction, and occupancy. The loads are shown in table II by season in terms of the energy required referenced to an indoor design temperature of 296 K (74° F). In addition, yearly heating and cooling peak loads that occur on "design" winter and summer days are used to size the equipment installed. These loads are 3400 kilowatts (11.8×10^6 Btu/hr) for heating and 3810 kilowatts (1084 tons) for cooling.

Brayton-cycle-engine and fuel cell recovered heat, which is usable for HVAC functions, can be divided into temperature ranges of 339 to 394 K (150° to 250° F) and greater than 394 K (250° F). Solar collectors are assumed to cover 80 percent of the total roof area of each apartment complex building at a fixed slope of 40° (the approximate latitude of Washington, D.C.) and are further assumed to supply hot water at 366 K (200° F) with a 63-percent collection efficiency. This reasonably attainable performance should be achievable in the next few years (ref. 1). The clear day solar insolation values (ref. 2) were adjusted for seasonal averages, surface angle, and effect of average cloud cover. The seasonal recovered heat from the three sources is shown in table II.

In matching the recovered heat with the load requirements, the domestic hot water was assumed to have an initial temperature of approximately 289 K (60° F) and to require heating to 339 K (150° F). The temperature required for space heating is flexible in the 339- to 394-K (150° to 250° F) range because temperature drop and fan coil size are

variable. For space cooling, existing absorption chillers require hot water or steam at a temperature of approximately 394 K (250° F). However, low-temperature absorption chillers are being developed, and units capable of using water at a temperature of 355 to 361 K (180° to 190° F) and operating at a coefficient of performance of approximately 0.5 should be available soon (ref. 3).

The average seasonal results of matching recovered heat to load requirements are shown in table II. The results are based on using a water tank for thermal storage of either recovered heat on cool days or chilled water produced by the air-conditioning units on warm days. The seasonal energy comparisons show that there is sufficient recovered heat energy to meet the total HVAC requirements during fall, winter, and spring. During the average summer day, compression chillers are required to provide approximately 40 percent of the air-conditioning.

For the worst-case conditions, on a design winter day, 73 805 megajoules (70×10^6 British thermal units) of energy must be provided from thermal storage to meet space-heating and domestic hot water demands. On a design summer day, again using thermal storage, approximately 64 percent of the air-conditioning demand must be provided by compression chillers. Consequently, of the total air-conditioning peak demand of 3810 kilowatts (1084 tons), 2443 kilowatts (695 tons) of compression and 1371 kilowatts (390 tons) of absorption must be installed.

Water Treatment

The water subsystem provides potable water and wastewater treatment for the apartment complex and for the utility system. Potable-water loads include residential demands for kitchen, laundry, bath, and toilet functions and exterior demands for recreational use (swimming pools) and for carwashing. The potable-water usage was determined assuming use of low-water-consumption devices, which reduce water requirements for showers and toilets by 90 and 30 percent, respectively. Variation of potable-water loads with seasonal exterior demands produces average daily water usages of 447 m³/day (118 000 gal/day) in the summer, 420 m³/day (111 000 gal/day) in the fall and spring, and 397 m³/day (105 000 gal/day) in the winter.

For potable-water treatment, the design is dictated by the nature of the water source; the advanced IUS water system (which is essentially a conventional system) has a capacity of 130 percent of the average daily demand. For a surface water source, the system includes chemical clarification, filtration, and chlorination processes. For

a ground water source, the chemical clarification and filtration steps are not required. A simple settling tank having a 3-hour retention time may be added if necessary. Depending on the specific application of the IUS, potable-water treatment may or may not be required; if it is not included, no other subsystem is affected.

Wastewater loads include the residence demands but not the exterior demands. This load amounts to an average of 394 m³/day (104 000 gal/day). However, the water used in any blowdown process within the utility system, particularly in the cooling tower, must also be included. This load amounts to 42 m³/day (11 000 gal/day) for an average daily total of 436 m³/day (115 000 gal/day). The wastewater treatment effluent is retained and used for fire-protection storage, for irrigation of the apartment complex grounds, for cooling-tower makeup water, and for a small amount of other MIUS process-water makeup. The fire-protection storage is sized at 2328 cubic meters (615 000 gallons), an amount based on requirements in the National Board of Fire Underwriters Handbook. This capacity will more than satisfy the requirements for irrigation and heat rejection which, again, are seasonal and peak in the summer at 17 and 129 m³/day (4400 and 34 000 gal/day), respectively. These loads also account for reductions in the potable-water demand as a result of reuse.

Wastewater treatment design requires an effluent quality acceptable for both discharge to the environment and reuse for process water and irrigation. Again, the design capacity is 130 percent of the average daily demand. The processes are illustrated schematically in figure 7. Key components that interact with other subsystems include the sulfur dioxide and oxides of nitrogen scrubbing towers, which remove the pollutants from the power generation exhaust gases; the effluent holding tank, which retains the treated wastewater for reuse in utility system processes and in irrigation and holds 2328 cubic meters (615 000 gallons) firewater; and the sludge drying (dewatering) unit, which uses a solvent for extracting solids from the liquid and thereby reduces the volume of sludge for ultimate disposal in the solid waste subsystem. The sulfur dioxide scrubber (including the iron contact tank), the oxides of nitrogen scrubber, and the sludge dewatering technique are currently in the development stage. The other processes exist.

Architectural Energy-Saving Techniques

In addition to the HUD ground rule that MIUS components be currently available equipment, no changes in conventional architectural practices were permitted in buildings to be served by the MIUS. This limitation facilitates comparisons

between the MIUS and conventional utilities but prevents achieving additional energy and water savings. Although water loads were reduced, the analyses of the advanced IUS were performed using the electrical and HVAC loads from the baseline MIUS design. This method did facilitate energy comparisons, which are presented in the following section. However, the extent to which building energy loads could be reduced through architectural innovations and building-system changes also was investigated. These investigations did not include certain items normally subject to architectural design but treated in the previous utility system discussions (e.g., reduction of hot water demand and alternate HVAC systems).

At the start, a comprehensive list of candidate energy-conserving techniques was compiled as shown in appendix C. These techniques then were analyzed to determine their energy and cost impacts. Credible energy-saving methods that did not adversely affect lifestyles were considered viable. Energy loads computed for the baseline MIUS system were used to determine potential energy savings attainable through the use of candidate techniques. Then, the following constraints were applied.

1. The energy saved had to be significant (i.e., more than 1 percent).
2. The method had to be economical and marketable, having no more than a 20-year life-cycle payback period.
3. The technique had to preserve an acceptable lifestyle in a 1980 urban environment.

In determining life-cycle costs, the following assumptions and computations were made.

1. Construction costs for 1980 were used and were assumed to escalate at 5 percent/yr from 1974.
2. Fuel costs for 1985 were used and were assumed to escalate at 7.5 percent/yr from 1974.
3. The fuel quantities saved were determined by computing the load savings in the apartment complex and then applying conventional-plant efficiencies. The efficiencies used were as follows: electrical power generation including transmission losses, 30 percent; boilers, 80 percent; compression-air-conditioning coefficient of performance, 4.0; heating distribution losses, 6.3 percent; and cooling distribution losses, 1.8 percent.
4. Reduction of capital equipment costs for conventional utilities was consistent with load reduction.

The simple life-cycle payback period for a technique then was calculated by dividing the capital cost of each modification by the yearly cost of the fuel saved. The following formula was used.

$$T = \frac{x(\Delta A - \Delta B)}{y \left[C \left(\frac{1}{D} \right) E \right]} \quad (1)$$

where T is payback time in years, x is the 1980 construction cost factor, A is the differential capital cost of the technique, B is the differential capital cost of a conventional utility plant based on the load reduction, y is the 1985 fuel cost factor, C is the energy saving in joules (British thermal units) per year, D is the conventional-plant efficiency, and E is the fuel energy cost per joule (British thermal unit).

Table III contains a list of reasonable techniques from the candidates (appendix C) for which life-cycle payback times were computed. For each technique, the table shows percent load reductions at the apartment buildings, the capital cost of the technique, and the cost of fuel saved annually. Figure 8 illustrates the aggregated effect of these modifications but, again, does not include items normally subject to architectural design but treated in the previous utility system discussions.

In summary, this investigation indicates that total annual energy load reductions of 14.6 percent can be achieved without any substantive changes in lifestyle, and that the additional capital cost caused by these modifications could be paid back in 4 years by the energy cost savings.

Consumables Analysis and Comparisons

An analysis was made of energy and water usage in the illustrated advanced IUS, and results were compared to the baseline MIUS system and to a typical conventional system. The seasonal and annual energy requirements for a conventional system, the baseline MIUS, and the advanced IUS are presented in table IV. The conventional system design assumed a 30-percent electrical power efficiency (including transmission losses). It was further assumed that a central HVAC plant would be located at the apartment complex and that the plant would use compression air-conditioning having a coefficient of performance of 4.0 for cooling and an 80-

percent-efficient boiler system for heating. The advanced IUS requires 19 percent less fuel annually than the baseline MIUS system and 46 percent less fuel annually than the conventional system (table IV).

A similar comparison for potable-water requirements and for treated wastewater effluent disposed of environmentally is shown in table V. The advanced IUS enables savings of 37 percent potable water compared to the baseline MIUS system and 44 percent potable water compared to the conventional system; the advanced IUS enables savings of 40 and 47 percent, respectively, in wastewater effluent.

The solid waste residue requiring disposal is essentially the same in both the advanced IUS and the baseline MIUS system. In both cases, approximately 394 625 kilograms (435 tons) of solid waste residue is removed annually. This value represents an 80-percent reduction of solid waste removal required in a conventional system.

If the architectural energy-saving techniques (items A, B and C, D, F, and G in table III) were implemented in conjunction with the advanced IUS, an energy saving of 54 percent compared to the conventional system could be achieved. Furthermore, if manual-defrost refrigerators and controlled-exterior-air-circulation techniques were included from table III, an energy saving of 59 percent compared to the conventional system could be achieved. The latter techniques were deleted because of the lifestyle and cost payback criteria, respectively, but would be viable considerations.

CONCLUSIONS

In this paper, the potential of an advanced integrated utility system has been investigated using an illustrative system by which technology assumed to be available in 1980 was applied to serve a hypothetical 992-unit apartment complex. This investigation produced the following conclusions.

1. An advanced integrated utility system could conserve approximately 20 percent more energy than an integrated utility system using current technology, and it could conserve approximately 45 percent of the energy now used by a typical conventional utility system.

2. If architectural energy-saving techniques were also introduced, the apartment complex could be served with utilities using approximately 55 to 60 percent less energy

than a typical current conventional system without any significant change in lifestyle.

3. The amounts of potable water required and treated wastewater returned to the environment could be reduced by approximately 44 and 47 percent, respectively.

4. A system having a multifuel capability can be designed to use any of several forms of fossil or synthetic fuels as available.

5. A wastewater treatment system can be designed to include processes which also remove sulfur dioxide and oxides of nitrogen from exhaust gases and thereby simultaneously enhance environmental quality.

6. Although cost estimates of the advanced integrated utility system were not determined, the capital and maintenance costs of the system will undoubtedly be high. However, these high costs should be offset by reduced operating costs attributable to the substantially reduced fuel use and to increased fuel costs; that is, rising fuel costs will increase the cost of operating conventional systems more than for the integrated system, which consumes less fuel.

In general, it is concluded that advanced integrated utility systems have a significant potential for reducing both energy and water resource utilization. Such systems represent a fertile area for future investigations by government and industry.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, November 26, 1975
386-02-00-00-72

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TABLE I.- DAILY PYROLYSIS GAS COMPOSITION

Gas	Volume, m ³ (ft ³)	Heating value, MJ (Btu)
Hydrogen	813 (28 720)	8 224 (7.8X10 ⁶)
Carbon monoxide	435 (15 360)	5 166 (4.9)
Methane	369 (13 040)	12 336 (11.7)
Ethane	29 (1 040)	1 792 (1.7)
Ethylene	134 (4 720)	7 380 (7.0)
Propane	29 (1 040)	2 530 (2.4)
Carbon dioxide	453 (16 000)	0
Totals	<u>2 262 (79 920)</u>	<u>37 428 (35.5X10⁶)</u>

TABLE II. - HVAC ENERGY ANALYSIS¹

[All values in MJ (Btu)]

Parameter	Season ²			
	Winter	Spring	Summer	Fall
Loads				
Domestic hot water	3449 (3.271x10 ⁻⁹)	3 526 (3.344x10 ⁻⁹)	3 526 (3.344x10 ⁻⁹)	3487 (3.307x10 ⁻⁹)
Space heating	7443 (7.059)	911 (-.864)	0	565 (-.536)
Space cooling	0	3 244 (3.077)	14 538 (13.789)	4165 (3.950)
Recovered heat energy				
Fuel cell	709 (-.672)	724 (-.687)	724 (-.687)	716 (-.679)
Turbine	7687 (7.291)	7 858 (7.453)	7 858 (7.453)	7773 (7.372)
Solar	7108 (6.742)	11 160 (10.585)	12 562 (11.914)	9644 (9.147)
Results				
Heat used for absorption cooling ³	0	6 490 (6.155)	17 618 (16.710)	8329 (7.900)
Compression cooling required	0	0	5 729 (5.434)	0
Excess energy	4612 (4.374)	8 816 (8.362)	0	5751 (5.455)

¹Analysis based on an indoor design temperature of 296 K (74° F).

²Seasons assumed to include the following months: winter, December to February; spring, March to May; summer, June to August; and fall, September to November.

³Coefficient of performance is 0.5.

TABLE III. - CONVENTIONAL UNIT COSTS AND PAYBACK TIMES FOR ENERGY-SAVING TECHNIQUES APPLIED TO A 992-UNIT APARTMENT COMPLEX

Energy-saving techniques	Load reduction, percent		HVAC load	Capital cost ¹	Annual fuel cost saved ²	Simple payback time, yr ³
	Total load	HVAC load				
A. Surface/volume ratio reduction ³	1.3	3.7		\$0	\$ 5 718	0
B. Double pane glass	1.3	3.7		93 936	5 718	16.4
C. Low-infiltration windows and doors	.9	2.6		238 274	3 954	51.5
Techniques B and C combined	(2.2)	(6.3)		(200 062)	(9 674)	(20.7)
D. Infiltration barriers in walls	1.2	3.3		0	5 120	0
E. Revolving doors, vestibules, weatherstripping	.2	.6		63 948	908	70.4
F. External window shading ³	3.5	9.8		40 354	9 564	4.2
G. 80-percent fluorescent lightings ³	6.4	5.9		64 804	51 674	1.3
H. Manual-defrost refrigerators	4.3	3.9		-91 982	39 036	0
I. Controlled exterior-air circulation	5.8	16.3		576 556	15 964	36.1
Total selected techniques ³	14.6	29.0		\$305 224	\$ 81 750	3.7
Total all techniques	24.9	49.8		\$853 746	\$137 656	6.2

¹See equation (1). Capital cost = $\pi(\Delta A - \Delta B)$; annual fuel cost saved = $\pi(C(1/D)E)$.

²Simple payback time is obtained by dividing the capital cost by the annual fuel cost saved.

³Indicates techniques selected as conforming to both life-cycle-cost and lifestyle constraints.

TABLE IV.- COMPARATIVE SYSTEM ENERGY REQUIREMENTS
 [Values in nJ (Btu)]

Season	System		
	Conventional	Baseline MIUS	Advanced IUS
Winter	47 657 (45.2X10 ⁻⁹)	29 838 (28.3X10 ⁻⁹)	24 461 (23.2X10 ⁻⁹)
Spring	42 807 (40.6)	29 627 (28.1)	24 461 (23.2)
Summer	49 976 (47.4)	33 739 (32.0)	25 726 (24.4)
Fall	42 596 (40.4)	29 627 (28.1)	24 461 (23.2)
Annual	183 036 (173.6)	122 831 (116.5)	99 109 (94.0)

TABLE V.- COMPARATIVE SYSTEM ANNUAL WATER REQUIREMENTS

[Values in mm³ (gal)]

Requirement	System		
	Conventional	Baseline MIUS	Advanced IUS
Potable-water demand	0.277 (73.1X10 ⁻⁹)	0.246 (65.1X10 ⁻⁹)	0.154 (40.7X10 ⁻⁹)
Wastewater effluent disposal	.244 (64.6)	.214 (56.6)	.128 (33.9)

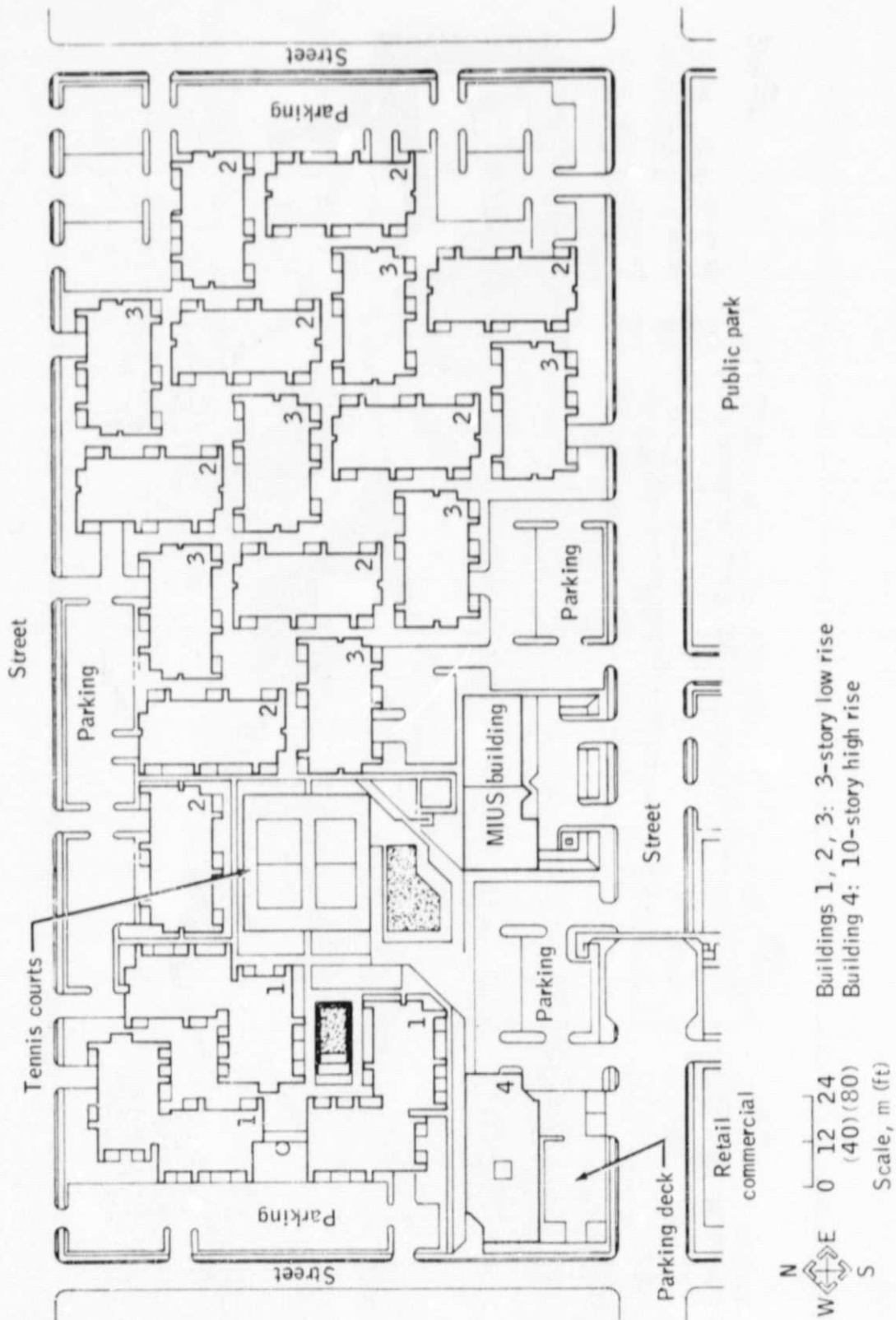


Figure 1.- A 496-unit apartment complex site plan.

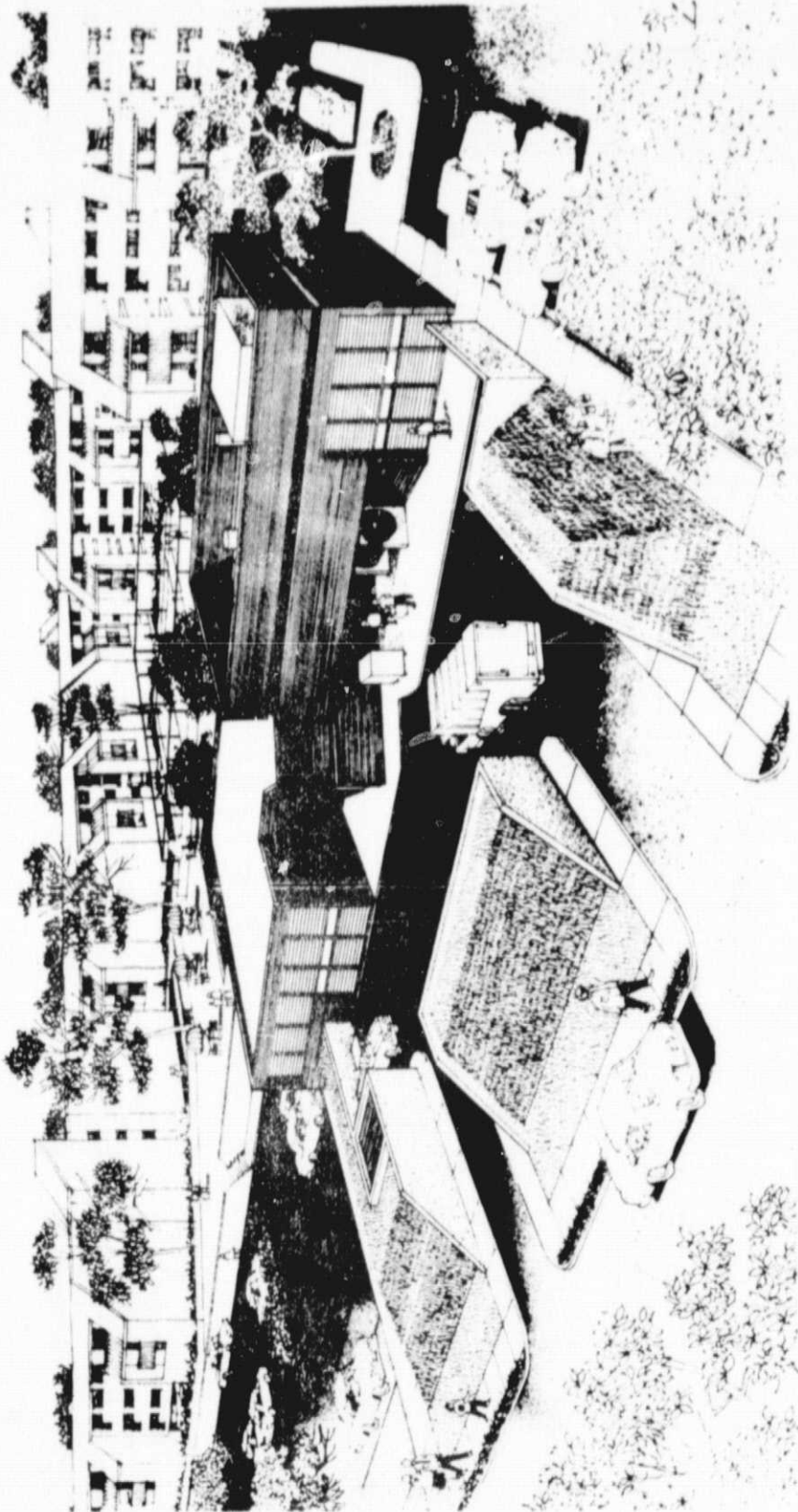


Figure 2.- Architectural rendering of MIUS plant.

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HX - heat exchanger

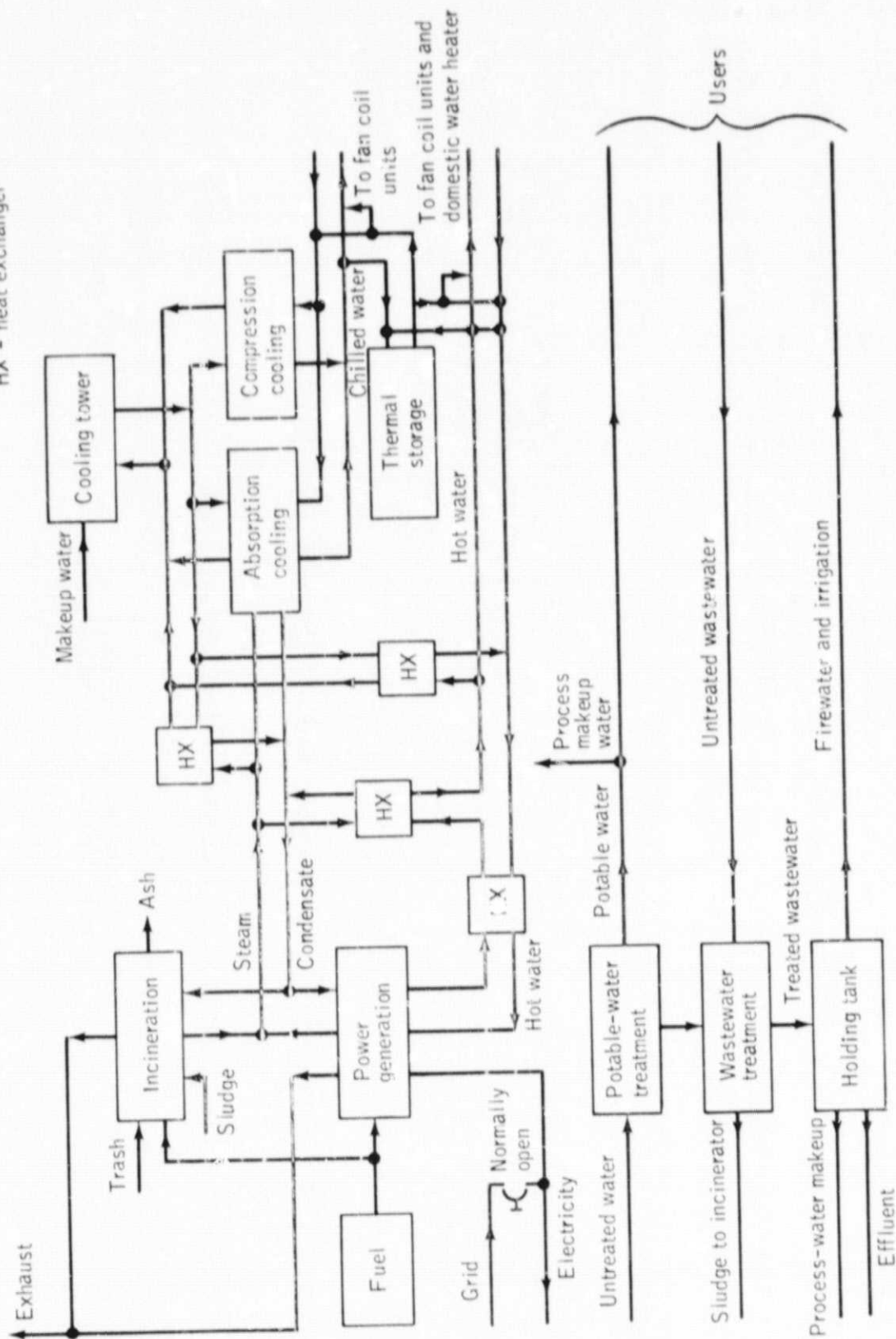


Figure 3.- Baseline MIUS overview.

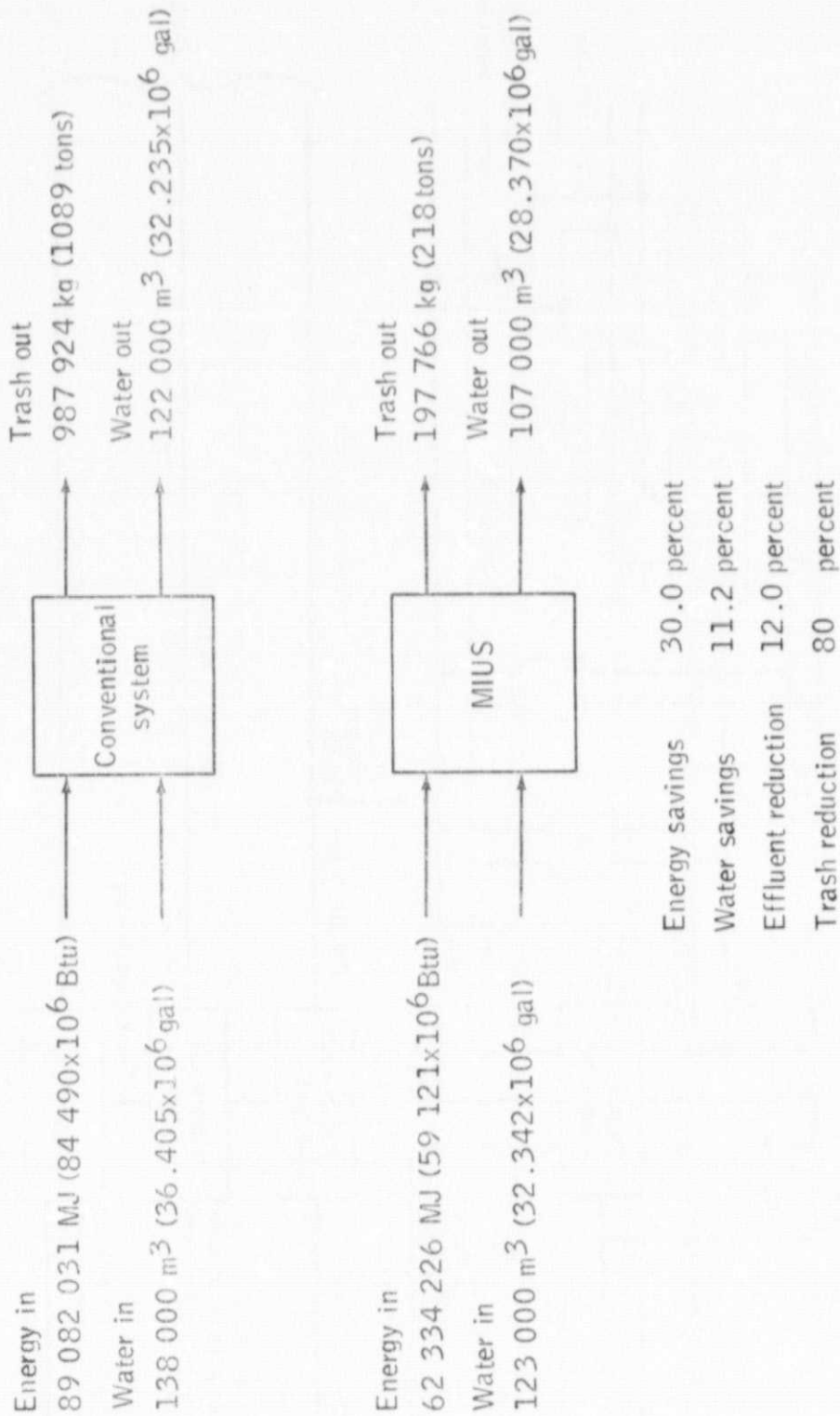


Figure 4.- Annual consumables comparison for a 496-unit apartment complex in Washington, D.C.

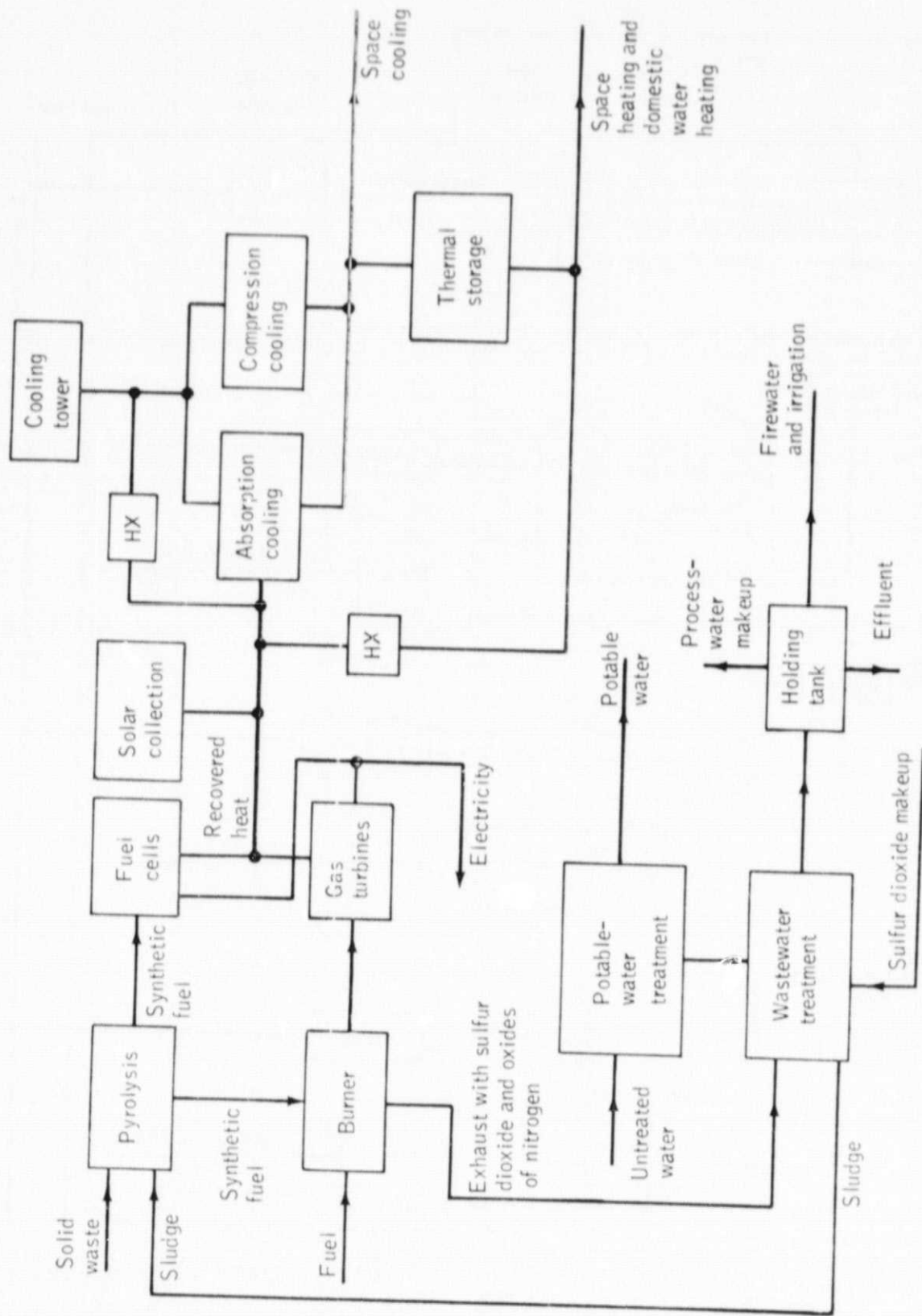


Figure 5.- Illustration of an advanced integrated utility system.

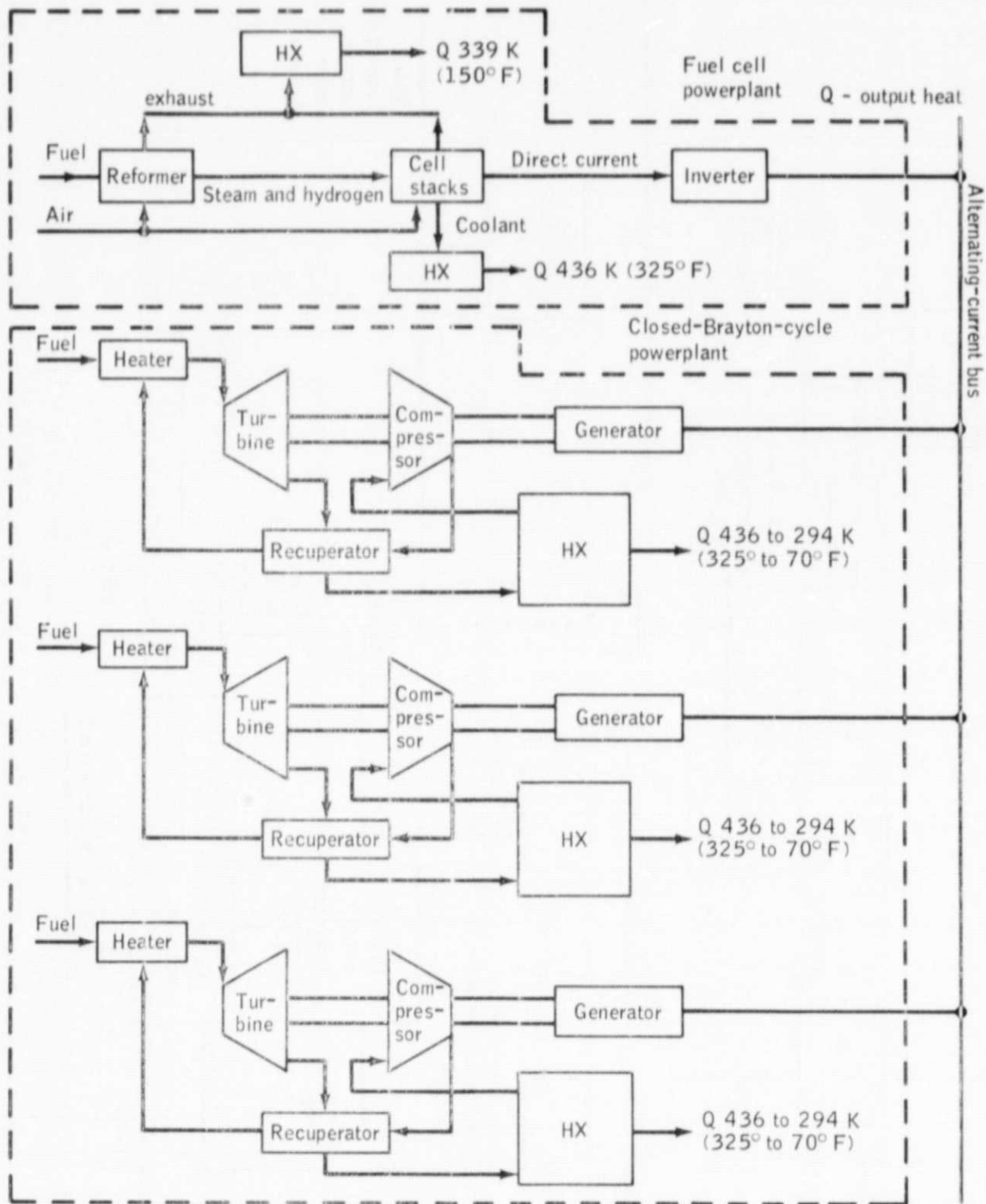


Figure 6.- Simplified functional block diagram of a power generation subsystem.

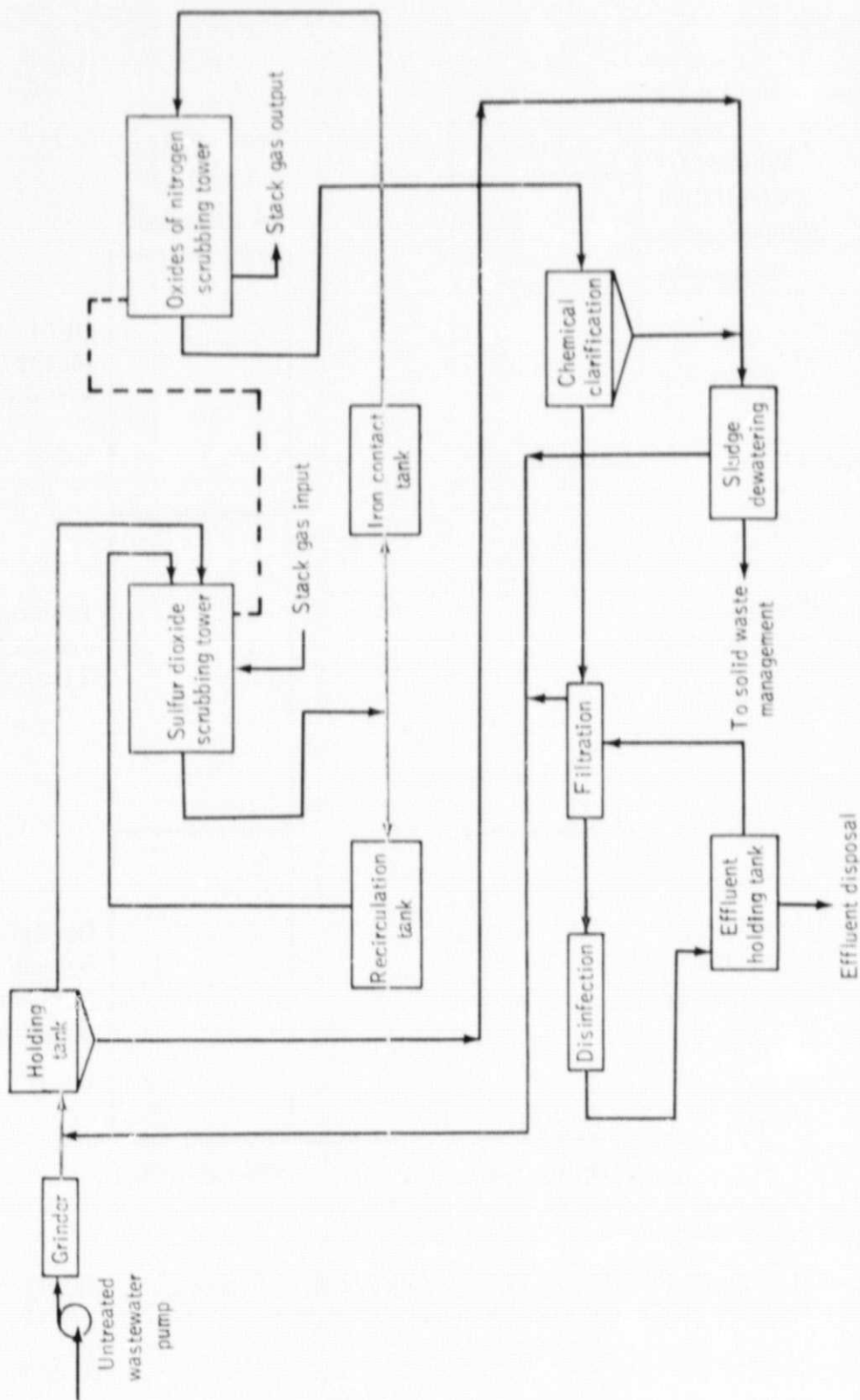
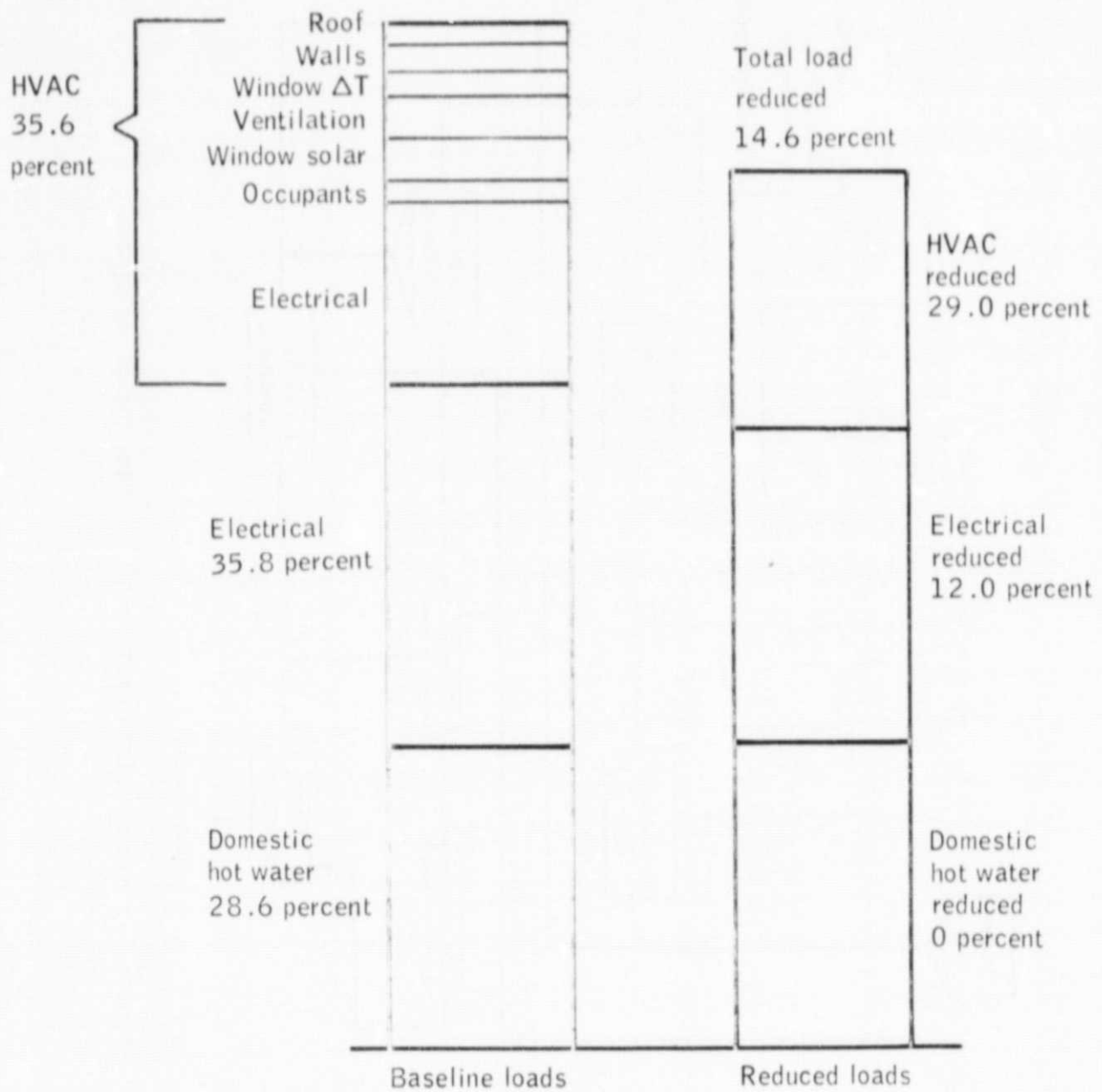


Figure 7.- Wastewater treatment system block diagram.



ΔT - differential temperature

Figure 8.- The effect of architectural energy-saving techniques (not including utility systems or low-water-use devices).

APPENDIX A

ILLUSTRATION OF A THERMAL STORAGE TECHNIQUE

By James O. Rippey

The following is a discussion of a thermal storage system (TSS) technique for cooling with particular emphasis on allowing for reduction in the installed electrical generating capacity. The illustration is for the baseline modular integrated utility system (MIUS) design for the 496-unit apartment complex. (The loads for the 992-unit complex are, of course, simply doubled.)

The design summer day total cooling loads and absorption/compression loads resulting from the baseline study are shown in figure A-1. The absorption chillers would be supplied 103-kN/m² (15 psig) steam from the prime movers and the incinerator after domestic hot water requirements were met. Distribution losses are added to the compression chiller requirements and equipment selected on the peak requirement during the design day, i.e., 859.7 kilowatts (244.6 tons) absorption and 1273.3 kilowatts (362.3 tons) (plus 34.1 kilowatts (9.7 tons) distribution losses) compression.

The design summer day electrical load components are shown in figure A-2. The domestic and auxiliary load profile without compression air-conditioning and the profiles with compression air-conditioning are presented. In the MIUS without cold thermal storage, the total demand reaches a peak of 1249.9 kilowatts at 9 p.m. and necessitates the use of three prime-mover/generator sets from 5 p.m. to 11 p.m. The introduction of the cold thermal storage capability allows only two prime-mover/generator sets to be used as shown at 104 percent of the rated load for 3 hours. Such equipment can be operated at overload conditions for short periods without adverse effects. Accordingly, chilled water is supplied for space cooling and storage in the more efficient early morning hours until a level in storage is reached (5623 kilowatts (1600 tons)) to meet the remainder of the design day requirements. Figure A-3 shows the revised design summer day cooling requirements with storage available. The compression capacity was raised from 1307 to 1406 kilowatts (372 to 400 tons) to ensure that storage would be completed before the demand period on storage occurred.

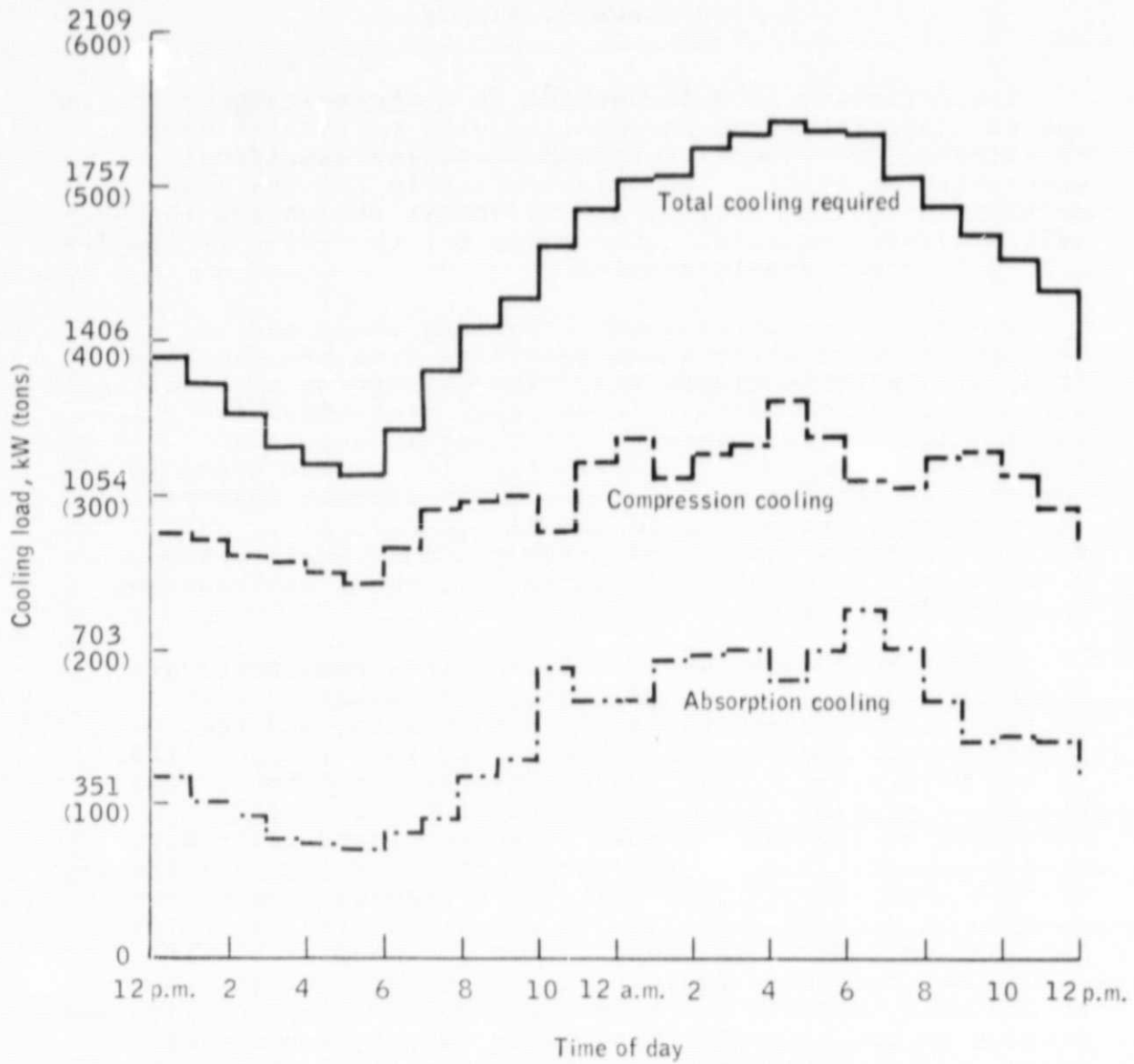


Figure A-1.- Design summer day total cooling load and absorption/compression loads without storage.

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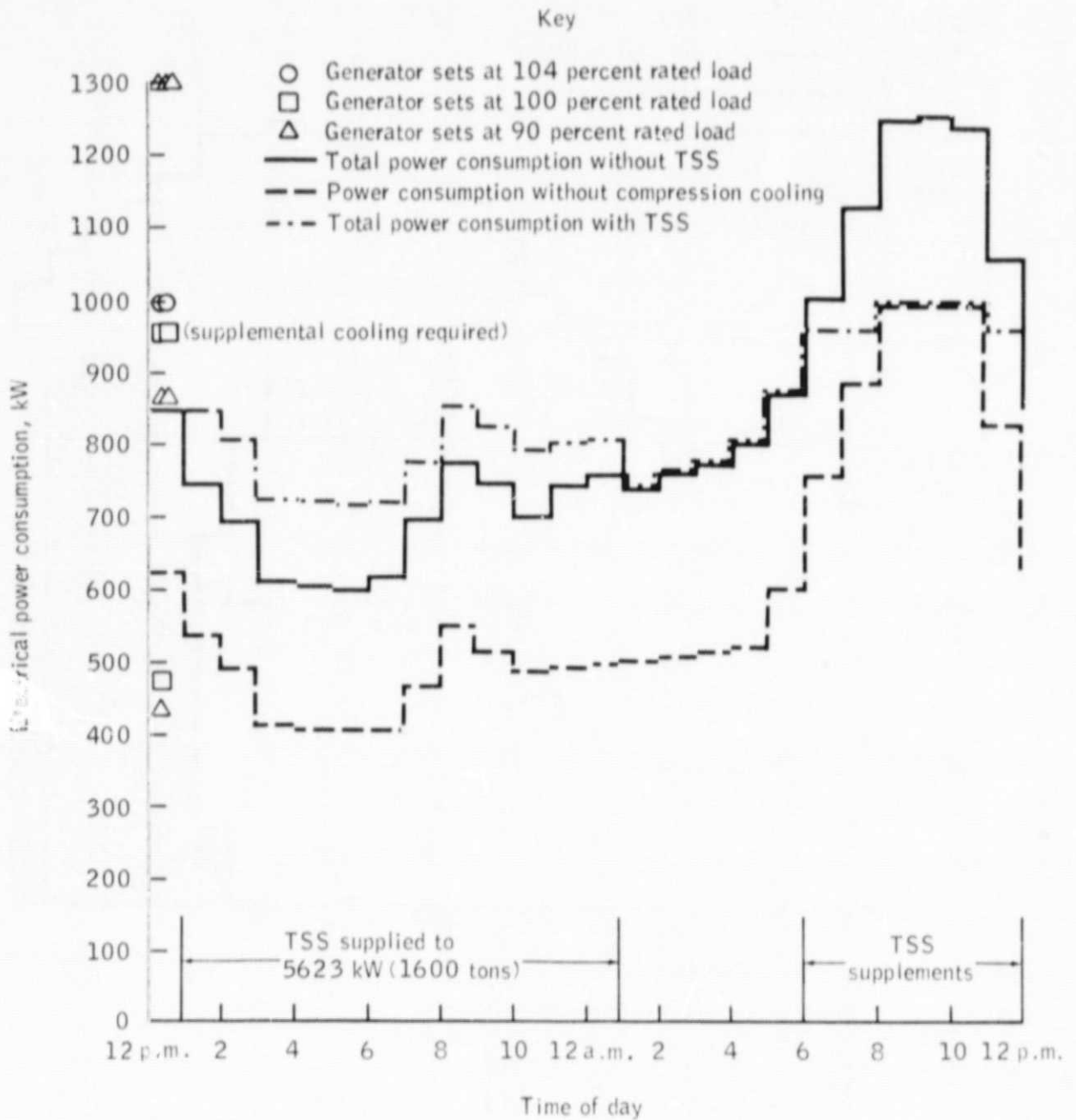


Figure A-2.- Design summer day electrical consumption.

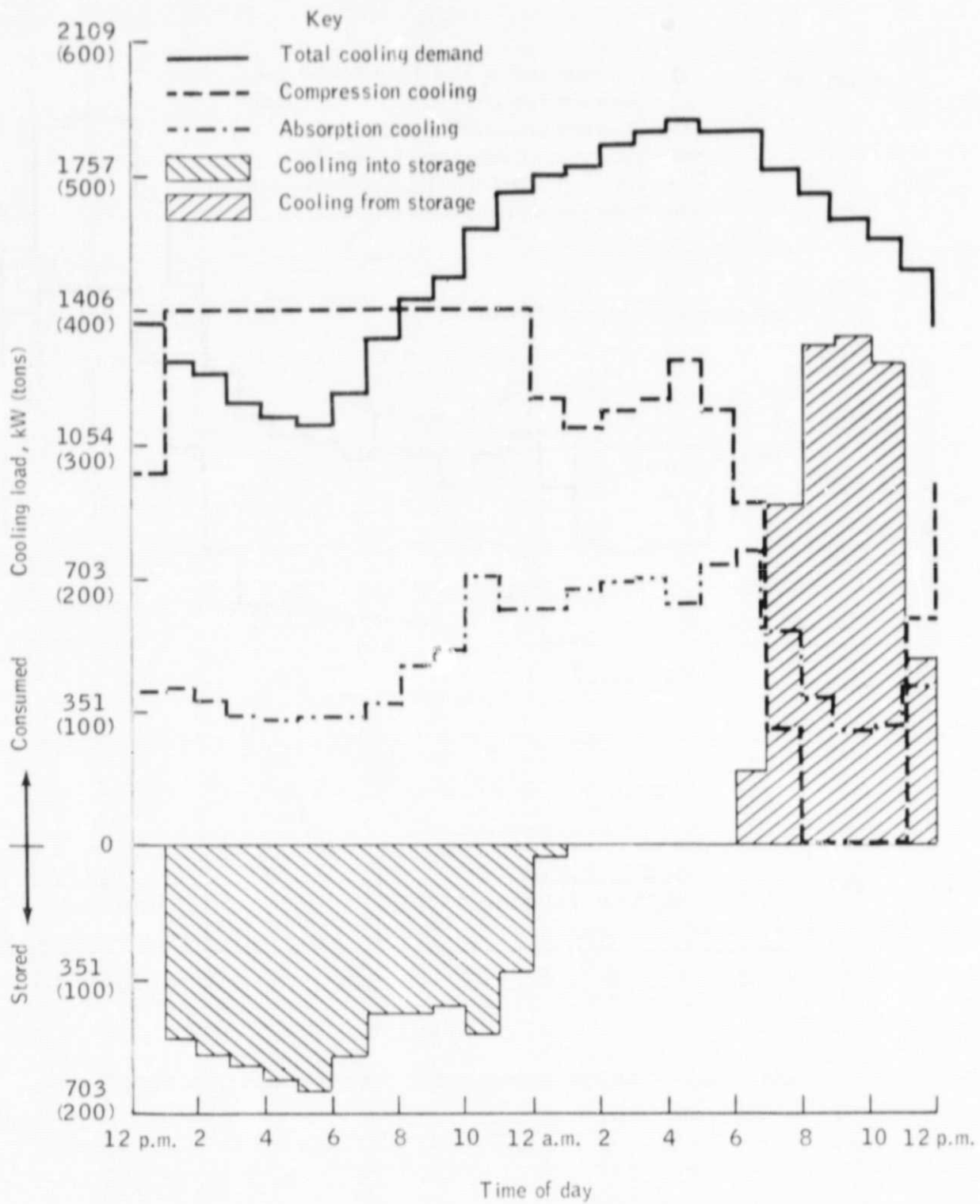


Figure A-3.- Cooling load distribution using storage.

APPENDIX B

COMMENTS ON FUELS

By Tony E. Redding

Because of the uncertainties surrounding future fuel availabilities, an advanced integrated utility system could provide a solution to the problem by offering a multiple fuel capability. That is, it would be desirable for the system to be capable of using any of the conventional fossil fuels and also solid wastes from commercial and residential sources. The fossil fuels may be either burned directly or preprocessed for use in power generation and heating equipment. Likewise, solid waste may be either incinerated directly or preprocessed to produce a liquid or a gaseous fuel. The options available for alternate fuels, possible end-use processes in integrated utility systems, and associated preprocessing requirements are shown in figure B-1, which indicates that, whereas gaseous and petroleum fuels can be used in virtually any type of power-conversion device, coal and solid wastes require preprocessing before use in any device other than external-combustion systems. Therefore, the most flexible and universal system concept, with respect to fuel use, would be an external-combustion power-conversion system. Also, the unique advantages of the fuel cell system (high efficiency, low pollutant emissions, quiet operation) can be obtained with all the fuels listed by means of preprocessing. For integrated utilities conceptual design purposes, therefore, a system incorporating external-combustion power-conversion sources or fuel cells (electrochemical power conversion) or both would be advantageous to demonstrate fuel source flexibility and system integration possibilities. As described in the section entitled "Electrical Power Generation," the closed-Brayton-cycle power system and the fuel cell have been selected for the design analysis.

Assumed heating values and fuel preprocessing efficiencies are shown in table B-1. The preprocess-efficiency values are based on the net calorific content of the cold (room temperature) product output. That is, the net efficiency is the heating value of the product gas (or liquid) at standard conditions divided by the gross heating value of the input fuel. It should be noted that the efficiencies given are typical only and that many process variables are involved, particularly with regard to the exact composition of the input fuel.

TABLE 3-1.- FUEL PROPERTIES AND PREPROCESS EFFICIENCIES

Fuel	Lower heating value ¹	Preprocess efficiency (net)
Petroleum (refined fuel oil), kJ/kg (Btu/lbm) ...	44 164 (19 000)	Gasification (low energy), 70 percent; conversion to hydrogen, 42 percent
Gaseous fuels (natural gas), kJ/m ³ (Btu/ft ³)	35 372 (950)	Steam reformation to produce hydrogen gas, 60 percent
Coal (typical), kJ/kg (Btu/lbm)	25 569 (11 000)	Gasification (low energy), 67 percent; hydrogen extraction, 62 percent ²
Solid waste, kJ/kg (Btu/lbm)	311 622 (5 000)	Pyrolysis (mixed hydrocarbon gases), 59 percent; pyrolysis plus reformation to produce hydrogen gas, 35 percent

¹As-received fuel.

²Theoretical value.

³Combustible metal and glass included.

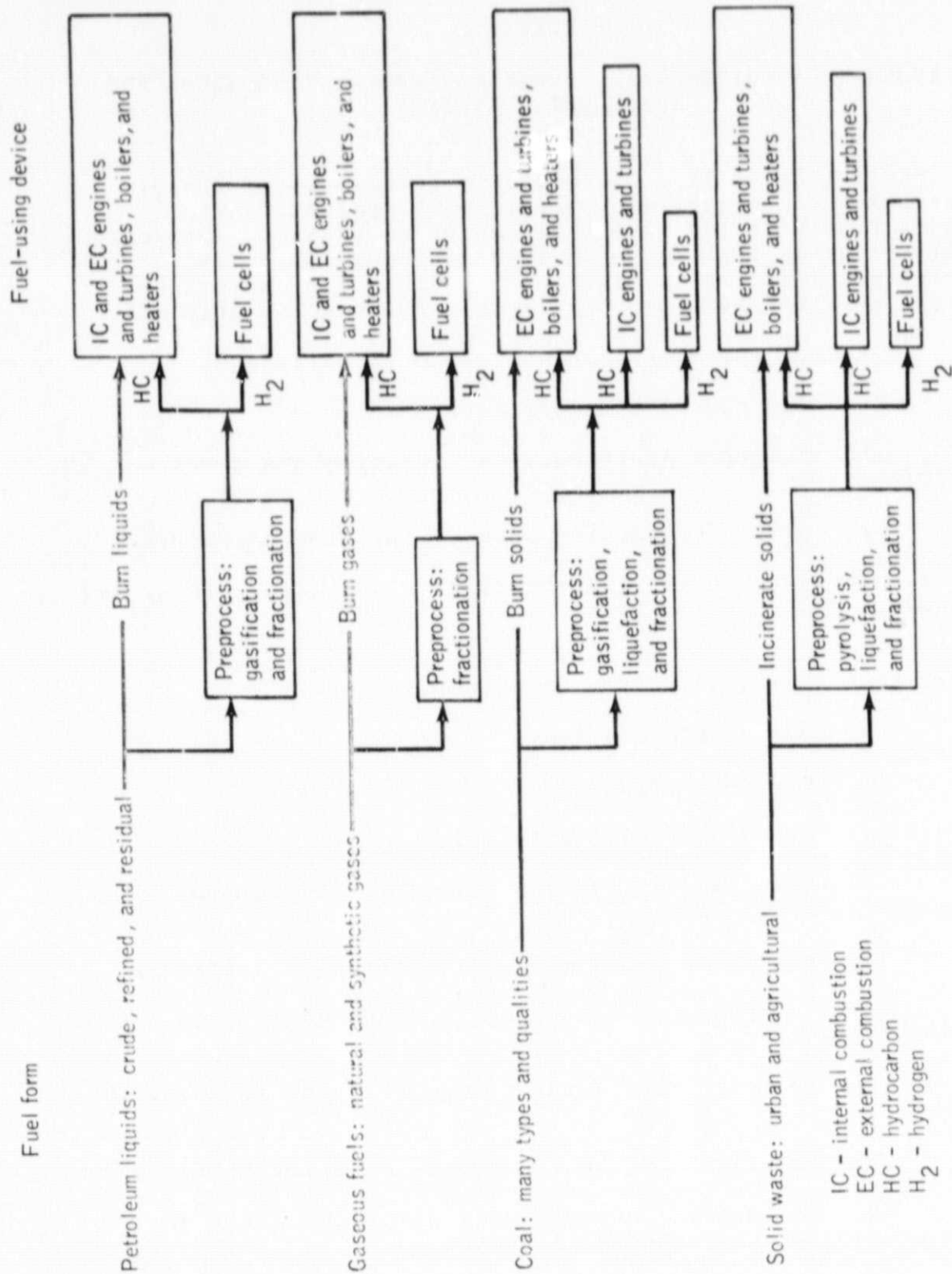


Figure B-1.- Flow diagram of alternate fuels and processes.

APPENDIX C

CANDIDATE ARCHITECTURAL ENERGY-CONSERVING TECHNIQUES FOR APARTMENT COMPLEXES

The following list of candidate architectural energy-conserving techniques was compiled for evaluation in conjunction with the investigation of an advanced integrated utility system applied to an apartment complex. The techniques selected as viable are indicated by asterisks. An analysis of these techniques is contained in table III.

1. Reduce surface-to-volume ratio of buildings.
 - *a. Use more compact designs.
 - *b. Use more apartments per building and fewer buildings.
 - *c. Eliminate parking beneath low-rise structures.
2. Improve thermal characteristics of walls, roofs, and windows.
 - a. Use more effective insulation and target for lower thermal-transmittance (U-value) factors.
 - *b. Use double glazing.
 - c. Use reflective glass.
 - d. Use denser wall materials.
 - e. Use heavily textured exterior finishes to increase air-film effectiveness.
 - f. Use earth berms along exterior wall surfaces.
 - g. Use roof areas for roof gardens with large planting areas.
3. Reduce solar heat gain in summer and/or increase in winter.
 - a. Use light (or dark) colored exterior surfaces.
 - *b. Use shading devices over all glass areas (to approach 100-percent shading in summer).
 - c. Increase shading of wall surfaces by more effective use of balconies.

- d. Orient buildings for solar heat gain.
 - e. Use trees, vines, and other landscaping elements for shading.
 - f. Reduce and/or shade paved areas adjacent to buildings to reduce reflected heat.
4. Reduce air infiltration through exterior surfaces.
- a. Use revolving doors in high-rise and entry vestibules in low-rise structures.
 - b. Weatherstrip all stair doors and seal all shafts to reduce chimney effect.
 - c. Orient buildings to reduce wind velocities.
 - d. Provide windbreaks at all entrances.
 - e. Design landscaping to establish windbreaks.
 - f. Use storm windows.
 - g. Use tighter building construction to avoid cracks and joints.
 - *h. Use building paper, plaster, or other air-infiltration barriers within walls.
 - *i. Use low-infiltration-rated windows and doors.
5. Reduce internal loads.
- a. Decrease the size of apartments by approximately 10 percent.
 - b. Provide for natural clothes drying on roof areas.
 - c. Use non-self-defrosting refrigerators.
 - d. Use ovens without self-cleaning elements.
 - e. Disconnect drying cycle from dishwashers.
 - f. Use microwave ovens.
 - *g. Use fluorescent lamps.
6. Change building systems.

- a. Reclaim waste heat from kitchens and bathrooms using heat exchangers.
- b. Recirculate air through activated charcoal filters.
- c. Reclaim heat from area ventilation exhausts.
- d. Circulate exterior air to the interior during cooling periods.

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