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Heat-Pump-Centered Integrated Community Energy Systems

System Development

Consolidated Natural Gas Service Company
Final Report

**ENERGY AND ENVIRONMENTAL
SYSTEMS DIVISION**

ARGONNE NATIONAL LABORATORY

OPERATED FOR THE U. S. DEPARTMENT OF ENERGY
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HEAT-PUMP-CENTERED
INTEGRATED COMMUNITY ENERGY SYSTEMS

System Development,
Consolidated Natural Gas Service Company, Interim Report*
Final Report

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PREFACE

More than one-quarter of the energy consumed in the United States is used to heat and cool buildings and to heat service water. Approximately 83% of the energy for these services is supplied from natural gas and oil. Recognition of the need to conserve these and other natural resources has been spurred, in large part, by the oil embargo of 1973 and subsequent escalation in fuel prices, by energy shortages, by increasing electricity "brown-outs" in urban centers, and by the crippling effects of labor strikes and stoppages in the energy supply industries. In recent years, development and acceptance of energy conserving systems which avoid dependence on scarce or interruptible fuels has increased markedly both in the United States and abroad.

Integrated community energy systems (ICES) are a comprehensive approach to increasing the efficiency of the varied ways in which energy is provided to and utilized by a community. ICES also offer opportunities to reduce dependence on scarce resources, protect environmental quality, reduce costs of energy and energy-consuming services, and, perhaps most importantly, meet energy needs without adversely affecting lifestyles.

The ICES approach to meeting these goals is embodied in three levels of integration. First, by incorporating innovative technology to maximize the resource-utilization efficiency, energy requirements can be reduced. Included in this method are cogeneration (or more precisely coproduction) and cascading uses of energy to minimize the thermodynamic mismatch of source-energy qualities and actual energy needs. Also included is fuel substitution in centralized community-scale systems which would be impractical in independent, individual-building and separate-service energy systems. Second, by integrating the energy and energy-consuming systems with the functional design and layout of the community, load-management advantages can be achieved and distribution losses can be minimized. At the same time, resource needs can be reduced through appropriate land utilization and planned growth. And third, the community systems development is integrated with the financial and regulatory mechanisms common to communities to permit widespread implementation.

A specific ICES may consist of either a partial or complete integration of these approaches, as appropriate to strike the desired balance among a community's economic, social, environmental, and energy-conservation goals. An ICES can be applied to a total community as well as to portions of a community and the services provided need not be the same for all areas served. While ICES include a broad spectrum of technologies to meet energy service requirements, the ICES concept does not arbitrarily define either the energy services to be provided or the type, size, or function of the area to be served. As a result, an ICES is tailored for each application. The determination of the kind and number of energy services provided and the size of the service area for each such service is based on an optimum combination of energy efficiencies, indigenous resource and labor supplies, economics, and environmental conditions.

Heat-pump-centered integrated community energy systems (HP-ICES) are energy systems for communities which provide heating, cooling and/or other thermal energy services through the use of heat pumps. Since heat pumps primarily transfer energy from existing and otherwise probably unused

sources, rather than convert it from electrical or chemical to thermal form, HP-ICES offer significant potential for energy savings. By powering these heat pumps with nonscarce fuels, the use of which would be impractical in most conventional systems, less-abundant fuels including natural gas and oil can be conserved. Secondary benefits of HP-ICES include reduction of adverse environmental effects as compared to conventional systems, reliable production of services in contrast to the increasingly frequent utility curtailments and interruptions, and delivery of services to consumers at costs lower than those for conventional systems (including acquisition, operation, and maintenance costs).

The report which follows a result of the System Development Phase of the HP-ICES Project. The objective of this multiphase project is development and demonstration of HP-ICES concepts leading to one or more operational systems by the end of 1984. The seven phases include System Development, Demonstration Design, Design Completion, HP-ICES Construction, Operation and Data Acquisition, HP-ICES Evaluation, and Upgraded Continuation.

This Project is sponsored by the Community Systems Technology Branch, Community Systems Division, Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Energy, U.S. Department of Energy (DOE). This particular study was cosponsored by the Technology and Consumer Products Branch, Consumer Products Division, Office of Buildings and Community Systems. It is a part of the Community Systems Program and is managed by the Energy and Environmental Systems Division of Argonne National Laboratory.

The report which follows presents the findings in the development and analysis of one concept under investigation. It was led by the Consolidated Natural Gas Service Company (CNG) which shared in the cost of the subcontracted effort. The Institute of Gas Technology (IGT), the principal subcontractor, performed the major portion of the analytical effort. Mechanical Technology, Incorporated (MTI), provided performance data on heat-actuated heat pumps, and Gamze-Korobkin-Caloger, Incorporated (GKC), advised IGT on certain aspects of heating practice and equipment costs. IGT provided most of the effort necessary in the preparation of this report.

Concurrently, DOE and CNG are conducting a development and demonstration program for the DOE/CNG gas-heat-pump system, under DOE Contract number EY-76-C-02-2883. The concurrent program was redirected in September 1977, toward "large"-tonnage applications; it is currently focusing on 60 to 400-ton buildup systems for multi-zone applications. Tests on a breadboard model of the pre-redirected gas-heat-pump system, sized for 7-1/2 tons, were completed by MTI in July 1978. Narrative reports corresponding to the DOE/CNG gas-heat-pump program are DOE technical documents numbers COO-2883-1 through 38.

This report is organized into sections according to the major emphasis given in general areas; considerable overlap of sections occurs because of the interaction of economics with other important elements. The first eight sections delineate the various aspects of this concept, while the final section presents in detail the thermal characteristics of buildings and their load data, energy costs, system component costs, central plant performance, and economic assumptions used in this study.

The major component in this HP-ICES is a central plant, which satisfies the heating, cooling, and domestic hot-water requirements for a "community" of buildings located in close proximity to the central plant. A distribution system of underground, insulated piping physically connects the HP-ICES utility to the community. The concept of a central plant providing thermal energy in some form to a distributed load requires that the community interact with the HP-ICES thermal utility in much the same way as it does with an electricity utility or gas utility: In return for providing a service to the community, the utility realizes some profit on its investment. The benefit which the building owners hope to enjoy the "hooking up" to the HP-ICES thermal utility results from the shift in responsibility (of meeting the building tenant's thermal requirements) from the owner to the HP-ICES utility. In return for their payments to the HP-ICES utility for this thermal energy, the owners are relieved of the burden of owning, operating, and maintaining the conventional equipment that would have otherwise been installed. The financial benefits are extremely dependent upon the cost of energy and the cost of transmitting the thermal energy from the plant to the community's buildings.

The heat-actuated heat pump (HAHP) results from the coupling and thermal integration of a natural gas-fired steam generator/turbine with a heat pump unit, comprising a refrigerant compressor, condenser, and evaporator. Thus, the HAHP provides heating and cooling by the utilization of both heat and shaft work. The motor/generator set may be used to drive additional cooling capacity; conversely, when the heat pump machine does not require the turbine's full work output, the set is used to generate electrical power for the overall system's parasitic (fans, pumps, etc.) loads. The central plant's peak heating capacity is raised by the addition of a supplemental boiler, which may be used in parallel with the turbine exhaust heat.

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EXECUTIVE SUMMARY

The Heat-Actuated Heat Pump Centered Integrated Community Energy System (HAHP-ICES) is a concept which utilizes a gas-fired, engine-driven, heat pump to supply the heating and cooling requirements of a community of residential and commercial buildings; and offers several advantages over the more conventional equipment it is intended to supplant. In general, the use of such a system, when compared to conventional equipment, will result in an overall reduction in the amount of energy consumed in meeting the various heating, cooling, and domestic hot-water demands of the community being served.

Two very different communities were used to provide thermal loads for the central plant in this study, thereby establishing the bases for the general and site-specific applications of the HAHP-ICES concept. The general non-site-specific application assumes a hypothetical community of one 59,000 ft² office building and five 24-unit, low-rise apartment buildings located in a region with a climate similar to Chicago. This community serves as a starting point — the base case — upon which various sensitivity analyses were performed and through which the performance characteristics of the HAHP were explored. The results of these analyses provided the selection criteria for the site-specific application of the HAHP-ICES concept to a real-world community. The site-specific community consists of 42 townhouses; five 120-unit, low-rise apartment buildings; five 104-unit high-rise apartment buildings; one 124,000 ft² office building; and a single 135,000 ft² retail building located in Monroeville, Pa.

The base-case analyses confirmed that the HAHP-ICES has significant potentials for reducing the primary energy consumption and pollutant emissions associated with space conditioning when compared with a conventional system. Primary energy consumption was reduced by 30%, while emission reductions ranged from 39% to 77%. Tables ES-1 and ES-2 display these findings.

The economic analysis of the base case was constrained so that the owners of the buildings in the community, at most, experience the same life-cycle cost as with owning and operating conventional HVAC equipment. The investors in the HAHP-ICES central plant receive a rate of return equivalent to that earned by the most profitable gas and electric utilities. When the base-case economic results precluded each of the above constraints being met, a series of sensitivity analyses were performed. These analyses identified several system design parameters which, when appropriately varied, resulted in an economically feasible application. These parameters may be summarized as follows:

- Thermal Load Selection: Communities with a larger ratio of heating to cooling requirements (3:1 or greater, preferably including a cooling season heating load, such as domestic hot water) were found to yield economically acceptable results.
- Climate Choice: Regions featuring a high number of heating-degree-days are favorable to the economics of the system. This is not a restrictive condition, community thermal load selection can offset undesirable climatic aspects.

- Energy Cost Constraints: A relatively high cost of energy (either electric power or gas, or both) will result in more favorable economics for a HAHP-ICES application.
- Utility Rate Constraints: Structures which do not encourage energy consumption by offering disproportionate discounts in unit energy costs to large users are favorable to the HAHP-ICES economics.

Table ES-1. ENERGY CONSUMED BY CONVENTIONAL AND HAHP SYSTEMS IN PROVIDING THE BASE-CASE COMMUNITY DEMANDS

<u>Heating & Cooling System Employed</u>	<u>Energy Consumed Per Year, 10⁹ Btu</u>			<u>Relative Primary-Energy Consumption</u>
	<u>Natural Gas</u>	<u>Electrical Power</u>	<u>Total Primary*</u>	
Conventional	11.20	4.75	15.96	1.00
HAHP-ICES	10.13	1.08	11.21	0.70

* Primary energy calculated assuming gas transmission efficiency of 95%, electrical power generation and transmission efficiency of 29.68%.

Table ES-2. ANNUAL BASE-CASE EMISSIONS RESULTING FROM USE OF CONVENTIONAL AND HAHP SYSTEMS IN MEETING COMMUNITY DEMAND

<u>Emissions</u>	<u>Annual Emissions, * lb/yr</u>		<u>Attributed to HAHP-ICES Reduction, %</u>
	<u>From Conventional System</u>	<u>From HAHP-ICES</u>	
Particulates	618	269	56
SO ₂	5094	1156	77
CO	385	223	42
Hydrocarbons	143	87	39
NO _x	3950	1803	54

* Emissions from gas-fired conventional heating units and utility produced electricity. Values reflect energy requirements for distribution losses, distribution pumping, and cooling tower loads. Utility system is assumed to be 77% coal, 18% oil, 2% gas, and 3% nuclear with a busbar heat rate of 10,284 Btu/kWhr.

The site-specific case represents an application of the HAHP-ICES concept in a planned community under development in Monroeville, Pennsylvania. The Monroeville site falls in the mid-range of acceptable HAHP-ICES locations within the United States as deduced from the above system design parameters.

The results of the site-specific analysis indicate that reductions in energy consumption of between 15% and 22% are possible when a HAHP-ICES is selected as opposed to conventional HVAC equipment. The primary energy requirements of the conventional HVAC equipment and five selected cases (a highly efficient conventional district heating system and four cases which explore the sensitivity of the number of turbine-driven heat-pump units in the central plant to community energy consumption) are presented in Table ES-3. Compared with conventional HVAC equipment, lower pollutant emissions were experienced, corresponding to the reductions in energy consumption. The reductions varied from 20% to 81%; depending on the pollutant type and number of turbines.

Table ES-3. ENERGY CONSUMED BY CONVENTIONAL AND HAHP SYSTEMS
IN PROVIDING THE SITE-SPECIFIC COMMUNITY DEMANDS

<u>Heating and Cooling System Employed</u>	<u>Energy Consumed Per Year, 10⁹ Btu</u>			<u>Relative Primary-Energy Consumption</u>
	<u>Natural Gas</u>	<u>Electrical Power</u>	<u>Total * Primary</u>	
Conventional	57,971	16.248	74.219	1.00
HAHP-ICES				
0 turbine	57.491	10.429	67.920	0.915
1 turbine	56.141	6.639	62.780	0.846
2 turbines	56.550	5.000	61.550	0.829
3 turbines	55.648	3.882	59.530	0.802
4 turbines	55.248	3.032	58.280	0.785

* Primary energy calculated assuming gas transmission efficiency of 95%, electrical power generation and transmission efficiency of 29.68%.

The economic analysis shows that although the HAHP-ICES concept can offer highly attractive discounted cash flow rates of return (DCFROR) for potential investors, or potential cost savings to community members (as displayed in Tables ES-4 and ES-5, respectively), the zero turbine case (highly efficient conventional district heating system) yields slightly better results. The addition of the fourth turbine results in the DCFROR dropping to 24% (from 35% in the zero turbine case) and the payback period increasing to 3.7 years (as opposed to 2.6 years for the zero turbine case).

Table ES-4. DISCOUNTED CASH FLOW RATES OF RETURN* — SITE-SPECIFIC CASE

<u>Number of Turbines</u>	<u>DCFROR, %**</u>	<u>Payback of Initial Equity, yrs</u>
0	34.61	2.6
1	32.37	2.8
2	28.85	3.1
3	26.61	3.3
4	24.01	3.7

* Based on after-tax net cash flows.

** Discounted cash flow rate of return. The HAHP-ICES cost of service for community members is set equal to that of individual conventional space conditioning system ownership.

Note: The cost of the thermal distribution system and its associated losses has been incorporated into this analysis.

Table ES-5. POTENTIAL COST SAVINGS FOR COMMUNITY MEMBERS
(SITE-SPECIFIC CASE)*

<u>Number of Turbines</u>	<u>Potential Cost Savings**</u>
0	9%
1	9%
2	7%
3	7%
4	5%

* Potential annual savings to community members served by HAHP-ICES thermal utility in the cost of owning and operating individual, conventional HVAC systems.

** Rounded to the nearest whole percent. Predicated upon the fact that the investor would accept a 15% pre-tax rate of return on investment in the central plant.

Thus, a turbine-driven heat pump, while it saves energy, cannot totally pay for itself under the assumptions used in this analysis. The breakeven points for the economic justification of each case, in terms of a single energy escalation rate, are presented in Table ES-6. This single rate, a weighted average of gas and electricity cost escalators, obtained by multiplying the ratio of the cost of each energy type to the total cost of energy by the appropriate cost escalator, would have to be 11% to justify the estimated costs associated with the first turbine unit in this analysis.

Table ES-6. WEIGHTED AVERAGE ENERGY ESCALATION RATES.
REQUIRED FOR TURBINE CASE ECONOMIC SUPERIORITY

<u>Number of Turbines</u>	<u>Required WAEER,* %</u>
1	11.1
2	12.8
3	12.8
4	13.1

* Weighted Average Energy Escalation Rate.

Based on the projected housing needs of individual states and major metropolitan areas, there is an estimated annual potential U.S. market of about 390 residential/office real estate developments of the type and approximate size represented by the HAHP-ICES base case. There is no obvious basis for predicting the timing or the extent to which the HAHP-ICES concept might penetrate this potential market; however, scenarios based on different pessimistic-optimistic market capture assumptions suggest that the market penetration potential for the 1980-1990 period could vary from 3 to 411 systems (equivalent to 711 90-hp heat pumps). The realization of this potential would depend on such factors as tax incentives, energy regulations, and future cost considerations. The potential energy savings corresponding to this market penetration potential range would be 27×10^9 Btu/yr (4.7×10^3 bbl oil equivalents) and 3.7×10^{12} Btu/yr (6.4×10^5 bbl oil equivalents), respectively.

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1. SYSTEM DESCRIPTION

1.1 System Overview

The Heat Actuated Heat Pump - Integrated Community Energy System (HAHP-ICES) is a concept for a new type of venture in thermal utilities. The major component in this HAHP-ICES thermal utility is a central plant, which satisfies the heating, cooling, and domestic hot-water requirements for a "community" of buildings located in close proximity to the central plant. A distribution system of underground, insulated piping physically connects the HAHP-ICES utility to the community. The concept of a central plant providing thermal energy in some form to a distributed load requires that the community interact with the HAHP-ICES thermal utility in much the same way as it does with an electric utility or gas utility: In return for providing a service to the community, the utility realizes some profit on its investment. What makes the HAHP-ICES thermal utility unique, however, is that it must be competitive with conventional heating, cooling, and hot-water equipment which the various building owners could have installed from the beginning. Currently, electric and gas utilities do not have this type of competition; the building owners have no choice but to interact with these utilities, because there is no other means for generating power or producing gas. The benefit which the building owners hope to enjoy by "hooking up" to the HAHP-ICES thermal utility results from the shift in responsibility (of meeting the building tenants' thermal requirements) from the owner to the HAHP-ICES utility. In return for their payments to the HAHP-ICES utility for this thermal energy, the owners are relieved of the burden of owning, operating, and maintaining the conventional equipment that would have otherwise been installed. The financial benefits are extremely dependent upon the cost of energy and the cost of transmitting the thermal energy from the plant to the communities' buildings. These are issues which, in turn, are site-specific; they are, therefore, treated in a general manner in the base-case analysis, and directly in the site-specific case.

The basic component of the HAHP-ICES central plant is a steam turbine-driven heat pump. The steam generation and turbine provide a source of heat and shaft work; the heat pump may serve as a source for heating and/or cooling. Thus, the two units are the major sources of thermal energy for the community. The HAHP-ICES central plant is conceptualized in Figure 1.1. The addition of the motor/generator set allows the meeting of peak thermal demands (i.e., the set operating as a motor, driving additional refrigeration equipment) or the generation of power to meet the basic plant parasitic loads.

There are several advantages to integrating the thermal energy demands of a series of buildings that form a "community." There are both energy consumption and capital cost benefits to be derived by the use of a single, central source of heating and cooling for these buildings, as opposed to each having its own equipment for this purpose. By proper design (and sizing) of the central plant, it is possible that the turbine-based equipment can operate in a basically base-loaded (i.e., constant, full load) state. Peak demands, in excess of the baseload capacity, can then be met by the use of cheaper, less efficient units. In this regard, the HAHP-ICES thermal utility is not much different than electric utilities which prefer to baseload some units (e.g., nuclear facilities) and utilize oil- and gas-fired units for peak power demands wherever possible.

Figure 1.1. CONCEPTUALIZED HAHP-CENTRAL PLANT

In the following two major sections on the description of the base case and site-specific case, it must be noted that the size and composition of the "community" directly influences the overall performance and economic viability of the HAHP-ICES concept. The approach taken in this study was to first define a community and then design an entire HAHP-ICES around the community's thermal energy requirements. This description and analysis forms what is hereafter termed the "base case." Within this characterization of the base case is a description of the HAHP central plant; its design and operation remain, for the most part, unchanged in a more precise application of the concept to a specified community, which forms the site-specific case. It is, therefore, necessary to first describe the base-case community and then detail the HAHP central plant equipment. While seemingly out of order, it is the community which defines the central plant.

1.2 Base Case Description

The approach taken in the base case was to determine the performance of the HAHP central plant when serving a hypothetical, but nonetheless realistic, community, and then detail the effect of other factors which permit an assessment of the concept to be made in general, non-site-specific terms.

While this general overview of the HAHP-ICES is intended to be non-site-specific, the system's overall performance and economic viability are very difficult to determine without describing the various loads it is intended to meet. In other words, what type of buildings are contained in the "community?"

As will be detailed in a later section, at least one of these buildings must be able to use a "low" temperature (approximately 120°F) source of heat for meeting its thermal loads. At these supply temperatures, the only type of equipment which can provide space heating is the fan-coil terminal unit, which is basically a finned heat exchanger with an air blower. These units are typically found in office buildings, for perimeter heating when heat recovery from a cooling system is employed. Residential units on the other hand do not normally use fan-coil units, since they are more expensive than base-board systems and heat recovery from cooling is generally not available. Thus, it would seem that the most likely candidate for the low-temperature heat from the central plant would be an office building. Its inclusion in the community does have one drawback, however: Offices are intermittent loads because they are usually only occupied 8 hours per day, 5 to 5-1/2 days per week. Therefore, in order for the HAHP-ICES to be realistically evaluated, other, more constant loads needed to be added to the community. Low-rise apartment buildings, located in close proximity to the office, are not difficult communities to envision. Detailed analyses conducted in the course of this study, and the general experience of heating, ventilation, and air conditioning (HVAC) contractors, have demonstrated that the use of fan-coil terminal units in low-rise residential buildings is difficult to justify on an economic basis, no matter what the source of heat. It was during this earlier analysis that the basic configuration of the central plant, and the mix of building types in the community, were selected. The use of fan-coil units in residential buildings allowed the earlier designed HAHP-ICES central plant to operate in its most economic and efficient mode; that is, the main heat-producing equipment operated in a base-loaded state. The community which provided the central plant with this thermal load consisted of the following:

- One office building, six-stories, 59,000 square feet total floor space
- Five low-rise apartment buildings, each with 24 dwelling units.

The thermal outputs from the central plant, in the form of chilled water and "low" and "high" temperature heat, supply the community's thermal requirements as shown in Figure 1.2. The office building's heating, cooling, and domestic hot water loads interface with the central plant equipment via variable air volume (VAV) terminals, fan-coil units and DHW heat exchangers. Because these office loads are contiguous to the central plant, a thermal transmission and distribution network, such as that shown for the residential buildings, is not required. Each apartment building is grid-connected by the thermal distribution system to the central plant located some distance away.

An artist's conception of the community is shown in Figure 1.3. The HAHP-ICES central plant is located in the lower floor of the office building. This selection was made for several reasons: First, a realistic assessment of the HAHP-ICES concept requires that it be compared, both in performance and economic terms, with the conventional HVAC equipment it is intended to supplant. Thus, a conventionally equipped office building would have a central equipment room to house its HVAC source units (i.e., boilers, chillers, etc.). There is much room for error in comparing this "conventional" office building with one that is designed without this equipment room and a displaced thermal utility building. It is much easier to compare two essentially identical office buildings, one containing HVAC source equipment and the other containing HAHP-ICES equipment. The owners of the office building realize no income from that equipment room, no matter what, or who, occupies it.

The second reason for this selection of the central plant's location results from the nature of the HAHP-ICES, and all heat pumps in general: The higher the temperature of the source for the "pumped" heat, the better the performance of the system in meeting its heating demands. Having an office building in the community presents a high-temperature (compared with the ambient air) source for heat pumping, that is, the wintertime cooling load which office buildings typically produce in the interior spaces. These areas are producers of heat because of equipment, lighting, personnel, etc., and do not have the heat loss rates exhibited by the exterior offices within the building. This interior wintertime cooling requirement is one thermal source for the HAHP-ICES plant. Therefore, the office building has a four-pipe thermal distribution system: Two for heating supply and return, and two for cooling supply and return. The cost of installing a piping system of four underground insulated pipes, running from the central plant to the office building, is significant and would be avoided by locating the plant inside the office building.

In the development of the ICES system design, the size and mix of buildings in the community were selected so that full use could be made of this wintertime office cooling load. The six-story office building selected for the community satisfies this wintertime cooling load criteria. Its summertime cooling load is far in excess of the central plant's capacity and, therefore, compressive chillers were added. However, the central plant produced much more heat than the office building could use. The resulting system, therefore, had excess heating capacity but no excess cooling capacity. The residential buildings (24 units each) were then added to the system until the office and

Figure 1.2. CONCEPTUALIZED BASE CASE COMMUNITY INTERFACE WITH HAHF CENTRAL PLANT. THERMAL DISTRIBUTION NETWORK OWNED BY THERMAL UTILITY. ON-SITE HVAC EQUIPMENT PRIVATELY OWNED.

1-6

Figure 1.3. ARTIST'S CONCEPT OF BASE CASE HAHP-ICES COMMUNITY

residential average heating loads equaled the central plant's heat pump capacity. (Note that no cooling is supplied to the residential units because the central plant's cooling capacity was sized just sufficient to meet the office building's requirements only.)

While the procedure for assembling the mix of buildings in the community was based on a different central plant design and operating guidelines, this same community remains unchanged in the current study. It may not be stated that this community will be the best possible one that could be assembled. The only test for whether this community allows the central plant to operate in a "base-loaded" state is whether or not a significant amount of wintertime heat is provided by the basic heat pump portion of the plant. This will be true if, on the average, the central plant can meet the heating loads imposed on it, with a "respectable" coefficient of performance (COP), defined here as -

$$\text{COP} = \frac{\text{heat supplied to the community}}{\text{natural gas consumed}} \quad (1-1)$$

If the plant needed to rely principally upon gas-fired boilers, the system's COP would approach 0.83, or the thermal efficiency of the boiler. This cannot be the case because the central plant supplied the community's heating demand for the months of January through March, using actual building load data and Chicago weather, at a system COP of 0.92. At this value, it is a safe assumption that the heat pump portions of the central plant are supplying a significant amount of energy to the community.

The residential buildings in the present design are heated by the use of baseboard terminal units in each dwelling unit. Depending on the outside ambient temperature, the HAHP-ICES central plant provides a heated fluid (such as water) to these units at temperatures between 140° and 190°F. The temperature of the fluid returning from the residential buildings forms the heat regulating means and ranges between 20° and 25°F lower than the incoming fluid. Each building uses a circulating hot-water system at 130°F as a source of domestic hot water (DHW), which includes water for washing, cooking, etc. This water is produced via a heat exchanger in each building using the same heated fluid as the baseboard units.

As described earlier, the office building uses fan-coil terminals to provide for space heating and cooling. The equipment operation and specifications are given in Section 3 (Expected Performance), but there are several design considerations which may be mentioned here. First, the temperature of the fluids transmitting the heat are much lower than those associated with the residential units. Second, it is the only building which is provided with chilled water for space cooling. Third, during the heating season, whenever possible, it is advantageous to utilize the office cooling load as a heat source for the heat pump.

1.3 Central Plant Description

In the following sections, the basic central plant is discussed from a technical and performance viewpoint, illustrating its potential in supplying thermal demands.

The HAHP-ICES central plant basic design is shown in Figure 1.4. In the following sections, the major equipment groupings are discussed separately so that their individual functions and potential interaction with the balance of the plant may be illustrated.

1.3.1 Steam Drive System

The primary source of energy for the entire plant is derived from the steam drive system, which is shown in Figure 1.5 and comprised of the following components:

- Natural gas-fired steam generator, 800 psi, 1050°F, 1.5×10^6 Btu/hr
- Steam turbines, two units, high- and low-pressure expanders with steam reheat in between
- Regenerator for boiler feedwater preheat
- Steam condenser, operating at temperatures between 150° and 200°F.

The Steam Generator designed by Advanced Mechanical Technology, Inc. was patterned after the compact mono-tube automotive boiler developed by the Scientific Energy System Corporation in the early 1970's. Through the use of small-diameter, thin-wall finned stainless steel tubing these units achieved specific weights of about 50 lbs per million Btu per hour and a volume of about 1 ft³ per million Btu per hour, including burner and blower. Despite the highly economical use of material, the Steam Generator is designed in accordance with the ASME power boiler code, and in particular, operates at stresses and temperatures within the limits recommended by ASME. The mono-tube design is extremely safe, containing only about a liter of water, and actually has less stored energy than many residentially sized low-pressure boilers. This steam generator, at a thermal efficiency of 83%, supplies 800 psig steam to the high-pressure turbine, which exhausts to the reheater at 35 psig. The lower pressure turbine has steam inlet conditions of 1050°F and 35 psig. Turbine outlet temperature is about 480°F, with the pressure dependent on the desired steam condenser temperatures. As may be seen in Figure 1.4, this steam condenser must operate at a temperature dependent on the temperature of the fluid supplying heat to the residential load. As will be discussed in Section 1.4, the temperature of this fluid depends on the ambient air temperature, and will vary between 190° and 140°F.

1.3.2 Refrigerant Circuit C₂

The main heat pump equipment is contained in Refrigerant Circuit C₂, which is comprised of the refrigerant compressor, evaporator, and condenser. While the steam turbines produce 90 hp, the net available to the compressor in C₂ is 78.76 hp, the difference accounting for losses and shaftpower parasitics. The refrigerant vapor is first compressed, and then condensed.

Figure 1.4. BASIC SCHEMATIC DIAGRAM OF HAHp-ICES CENTRAL PLANT

Figure 1.5.. SCHEMATIC DIAGRAM OF STEAM DRIVE SYSTEM

The heat of condensation provides energy to the office heating load, and may provide some energy to the residential heating load. The temperature of the refrigerant at the condenser varies between 130° and 145°F. The temperature selected reflects a trade-off: A higher condenser temperature allows the maximum potential usefulness for this heat, but it lowers the heat pump's COP, defined as —

$$\text{COP} = \frac{\text{heat available at the condenser}}{\text{shaft work into the compressor}}$$

As will be shown in the discussion of the various heating modes available in the central plant, the trade-off of temperatures versus COP is determined solely by the "residential loop" temperatures.

The source for the heat to be "pumped" by Circuit C_2 is at the evaporator. Two sources for this heat of evaporation may be used: The outside air source (contained as part of refrigerant Circuit C_1) or the load identified in Figure 1.4 as "office cooling load." Although an office building will require heat in the winter, the interior spaces in the building will usually require some cooling. This anomaly results from the fact that while heat is lost from the building through the exterior walls, the interior offices are generators of heat, the result of operating equipment, lighting, etc. This cooling load may be considered a high-grade source of heat for the evaporator, but it must be remembered that it is an intermittent source, available only during "working" hours.

1.3.3 Refrigerant Circuit C_1

The other thermal source for the heat pump of circuit C_2 is produced in refrigerant circuit C_1 . The compressor for this circuit is rated at 16 hp and compresses the warmed refrigerant vapor produced in the air source evaporator. As a result, the amount of heat available from this circuit is extremely dependent upon the ambient air temperature. Because the compressors for the C_1 and C_2 circuits are both driven by the same steam turbine, the optimal performance point for the coupling of the circuits requires a close match of heat out of condenser C_1 to heat into evaporator C_2 .

1.3.4 Refrigerant Circuit C_3

The equipment contained in circuit C_3 is used only for meeting cooling loads which cannot be satisfied by the heat pump unit of circuit C_2 . The 126-hp compressor is driven by the motor/generator set; thus, when this circuit is used, no power for the overall system parasitics and pumps may be generated. It must be noted, however, that because circuit C_3 is used only when circuit C_2 is already operating at full load (i.e., at 78.76 hp), there is no excess shaftpower available for power generation.

1.3.5 Auxiliary Boiler

The auxiliary boiler, like circuit C_3 , is a peaking unit which is brought onstream when the heating demand exceeds the heat pump/turbine exhaust available heats. It is rated at 2.5×10^6 Btu/hr and produces steam at about 300°F.

The fluid transmitting the thermal energy to the residential heating load splits between the steam turbine/C₂ condensers, and the auxiliary boiler condenser. Like that for the turbine exhaust steam condenser, the temperature of the auxiliary boiler condenser is determined by the required residential heating loop temperatures, as will be discussed in the following section.

1.4 HAHP-ICES Plant in Heating Mode

The temperatures of the fluids transmitting thermal energy to the office and residential buildings determine the various condenser operating temperatures. These condenser temperatures are selected so as to allow the maximum use of their heats of condensation in the residential loop. As shown in Figure 1.6, at ambient temperatures of 0°F or lower, the sendout temperature for the residential buildings is 190°F; this sendout temperature then decreases proportionately to 140°F at an ambient air temperature of 50°F. The 140°F sendout temperature is maintained at higher ambient temperatures, reflecting the minimum required for the domestic hot water heat exchangers located at the buildings. The temperature of the fluid returning from the residential buildings is always 25°F lower than that for the sendout at ambient temperatures below 30°F. Above 30°F, this temperature difference decreases to 20°F at 50°F ambient and remains at that ΔT . At higher ambient temperatures, the return from the DHW exchangers will vary between 130° and 135°F.

The temperatures of the loop carrying heat to the office building are lower than that for the residential buildings, reflecting the use of fan-coil units; these units can operate at much lower loop temperatures in satisfying the office loads than can the baseboard heaters in the residential buildings. The office loop sendout temperature is a constant 120°F, and its return temperature is regulated to remain at 100°F. The demands for domestic hot water at 130°F cannot be met using these loop temperatures; instead, they are supplied by a sidestream of the residential loop.

Maximizing the overall performance of the central plant requires that the refrigerant and steam condensers operate at temperatures which will maximize their thermal input to the building heating loops. This relationship is shown in Figure 1.7. The steam condensers always operate at 10°F higher than the residential loop sendout temperatures. This ΔT was selected so as to allow for a reasonable heat exchanger size. The 10°F temperature difference does, however, place a serious constraint on the operating temperature of the refrigerant condenser. At ambient temperatures of 30°F or higher, the condenser operates at 10°F higher than the residential heating loop return. Referring back to Figure 1.4, it may be seen that at these condenser temperatures, heat from the heat pump may be provided to both the residential and office heating loops. At a 30°F ambient temperature, however, the refrigerant circuit is operating at its temperature limit of 145°F. At lower ambient temperatures it becomes impossible to maintain a 10°F temperature difference between the residential return temperature and the refrigerant condenser. This means that the heat pumping portion of the central plant can no longer provide any heat to the residential buildings and, thus, its loads must be satisfied solely by the steam condensers. At these lower ambient temperatures, therefore, the refrigerant condenser temperature is lowered to 130°F, which is again 10°F greater than the principal load for the condenser — the office building. This lowering of the refrigerant condenser temperature also increases the amount of heat available because of the higher COP.

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Figure 1.6. RESIDENTIAL AND OFFICE TEMPERATURE SCHEDULE

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Figure 1.7. CONDENSER TEMPERATURES AND SENDOUT/RETURN SCHEDULE

The refrigerant, steam, and loop flows for the office and residential buildings when the central plant is in its heating mode may now be classified according to the heat pump thermal source. Figure 1.8 represents the operation of the HAHP-ICES using the office building cooling load as a heat source, with the ambient temperature of 30°F or higher; Figure 1.9 represents the same conditions with lower ambient temperature, the difference being in the use of the C₂ condenser heat. At higher thermal loads, the auxiliary boiler is brought into line, as shown in Figure 1.10.

At those times, such as evenings or weekends, when no office cooling load is available, the ambient air serves as a heat source for the heat pump portion of the central plant. Figure 1.11 represents its operation at ambient temperatures above 30°F, while at lower ambient temperatures, the flows of Figure 1.12 are used. The use of the auxiliary boiler is also required in this operating mode to meet peak demands as was shown in Figure 1.10.

1.5 HAHP-ICES Plant in Cooling Mode

Cooling demands of the office building are met by production of 44°F chilled water at the central plant. The return water temperature from the office building is assumed to be 55°F. The evaporator of Circuit C₂ is the primary source for this chilled water, while the steam turbine condenser is used to meet the year-round domestic hot water load, as shown in Figure 1.13. The heat released in the C₂ condenser is rejected to the environment via a cooling tower. Peak demands for cooling are met by the motor/generator set driving refrigerant compressor C₃ with the circuit's condenser heat rejected to the cooling tower, as shown in Figure 1.14. The activity of the different circuits are summarized in Table 1.1 as a function of ambient air temperature.

1.6 Site-Specific Case

In this initial work involving a system analysis of potential application for a Heat-Actuated Heat Pump - Integrated Community Energy System (HAHP-ICES), a specific community is to be selected and analyzed. In order to accurately and realistically test the concept's technical and economic feasibility, any such application should provide, at once, both a favorable and diverse load for the central plant. Conditions which should be considered favorable, in light of the base-case results, are cool climates, the potential for a year-round cooling load as a source for heat pumping, and gas and electric utility rate structures which do not favor high consumption.

A community which contains a diverse number of building types provides the subsequent analysis with a basis from which the true market potential may be estimated. A wide range of building type and function may also be considered more acceptable as a definition of a "community" to some than that selected as the base case. The specific site selected for this study must be one that is actually planned for construction, albeit not necessarily as an ICES community.

Table 1.1 COMPONENT ACTIVITY AS A FUNCTION OF AIR TEMPERATURE

Ambient Air Temperature	Thermal Source for Heat Pumping	Heating or Cooling Load on Circuit					Corresponding Figure
		C ₁ Air Source Heat Pump	C ₂ Primary Heat Pump	C ₃ Peaking Chiller	Turbine Ccndenser	Auxiliary Boiler	
< 30°F	Office Cooling Load	(off)	Office	(off)	Residential, DHW	(off)	1.9
	Office Cooling Load	(off)	"	(off)	"	Residential, DHW	1.10
	Ambient Air	C ₂ EVAP	"	(off)	"	(off)	1.12
30°F - 60°F	Office Cooling Load	(off)	Office, Residential, DHW	(off)	"	(off)	1.8
	Ambient Air	C ₂ EVAP	"	(off)	"	(off)	1.11
> 60°F	Office Cooling Load	(off)	Office	(off)	DHW	(off)	1.13
	Office Cooling Load	(off)	Office	Office	DHW	(off)	1.14

Figure 1.8: CENTRAL PLANT FLOW SCHEMATIC, OFFICE COOLING LOAD AVAILABLE, AMBIENT TEMPERATURE 30°F OR GREATER

Figure 1.9. CENTRAL PLANT FLOW SCHEMATIC, OFFICE COOLING LOAD AVAILABLE, AMBIENT TEMPERATURE LESS THAN 30°F

Figure 1.10. CENTRAL PLANT FLOW SCHEMATIC, OFFICE COOLING LOAD AVAILABLE
AMBIENT TEMPERATURE LESS THAN 30°F, AUXILIARY BOILER REQUIRED FOR PEAK LOAD

Figure 1.11. CENTRAL PLANT FLOW SCHEMATIC, AIR HEAT SOURCE, AMBIENT TEMPERATURE 30°F OR GREATER

Figure 1.12. CENTRAL PLANT FLOW SCHEMATIC, AIR HEAT SOURCE, AMBIENT TEMPERATURE LESS THAN 30°F

Figure 1.13. CENTRAL PLANT FLOW SCHEMATIC, BASIC COOLING MODE

Figure 1.14. CENTRAL PLANT FLOW SCHEMATIC, PEAK COOLING MODE

The community selected here for study as an HAHP-ICES application is in Monroeville, Pennsylvania. This development is planned for completion by 1983. The timing on its development is important in this study in that should this particular heat pump-ICES be selected for demonstration, sufficient time is allowed for the necessary design work to be performed before the actual construction work is initiated.

A 1983 completion date does, however, require that the proposed buildings be modeled as to their heating, cooling, and domestic hot water loads since the actual building designs are not yet available. Therefore, the community's building loads were estimated by use of other similar buildings, whose characteristics were already known as a result of previous studies by CNG, IGT, or GKC.

The Monroeville development is to be built on a 61-acre tract presently owned by the U.S. Steel Corporation, and is located about 20 miles due east of Pittsburgh. A conceptual design for the community is shown in Figure 1.15. The shopping complex is to be built parallel with Monroeville Blvd. and contains about 135,000 square feet of retail space. Near the center of the tract is the planned office building with about 124,000 square feet of floor space and six stories. The HAHP-ICES central plant would be located just northeast of the office building. A series of five high-rise (7-story) apartment buildings are to be found east of the office building and generally arrayed in a north-south direction. Farther east are the planned low-rise apartment buildings, each containing 24 dwelling units. Along the southeastern property border, 42 townhouses are scheduled, each with about 1000 square feet of floor space.

The locations for this community's buildings were selected by the developer, U.S. Steel Realty Development Corporation, to make full use of the site topography, which has a bowl-shape, with a valley running in a north-south manner on the eastern side of the tract. Existing homes between the property line and Hazelwood Drive, because of these elevation changes, would not be presented with visual barriers caused by the construction of multi-storied buildings, such as the offices or high-rise units. The location of the central plant was selected, for this study, so as to minimize the cost of the thermal transmission piping network. The darkened areas of Figure 1.15 represent green space and transitional buffer zones between the commercial and parking areas, and the residential areas. The open blank areas of the figure denote roadways and parking spaces.

The interface between the HAHP central plant and the community buildings is shown in Figure 1.16. As opposed to the community analyzed in the base case, where the central plant was contiguous to the office building, the Monroeville complex buildings are all separate from the central plant. In Figure 1.16, this separation requires a 6-pipe interface with the office building, and a 4-pipe interface with the high-rise units. The shopping center, low-rise apartments and townhouses have 2-pipe systems. Note that the shopping center receives heating or cooling, while the low-rise and townhouses receive heating for space conditioning and domestic hot water only. The high-rise apartments receive space heating or cooling, and are provided with domestic hot water. The cooling requirements for the low-rises and townhouses are met by use of thru-the-wall air conditioners, operated independently from the central plant.

Figure 1.15. SCHEMATIC VIEW OF MONROEVILLE ICS COMMUNITY

Figure 1.16. CONCEPTUALIZED MONROEVILLE ICES COMMUNITY INTERFACE WITH HAHF CENTRAL PLANT

The thermal distribution network schematic is shown in Figure 1.17. The network may be divided into two major systems: Mains and service connections. The mains form the bulk of the system and transmit the hot or chilled water either directly to a building (e.g., shopping center and office building), or to the service piping network which conducts the fluids to the individual residential buildings. Only one service connection is shown in Figure 1.17 for each block of townhouses for clarity; each dwelling unit requires a separate service connection. In total run of pipes, the mains comprise 6688 feet, while the service connections add about 2600 feet.

The basic design of the central plant does not differ much from that discussed for the base case. The much larger community examined here obviously does require a modification in the number and sizes of the central plant's equipment. The peak cooling (electric chiller) and heating (auxiliary boiler) equipment which are required were each split into two units with a ratio of capacity of about 3/1. This was considered preferable to one single peaking unit serving the entire community and operating a significant portion of the time in a low-load (and thus low-efficiency) state.

Central plants with 1 to 4 turbine/heat pump units were designed and analyzed (see Expected Performance and Economics sections) as a method in determining the optimal plant configuration and equipment size. In general, as the number of turbine/heat pump units is increased, the overall thermal efficiency increases, but the economic advantage over the conventional systems decreased. Because the issue of energy efficiency versus economic attractiveness is a choice for those who implement the HAHP-ICES, all four plant structures are discussed throughout this report. In all cases, the plant performance, sendout schedules, and basic control philosophies remain unchanged from those shown for the base case.

Figure 1.17. THERMAL DISTRIBUTION NETWORK PLAN FOR MONROEVILLE ICES COMMUNITY

2. POTENTIAL APPLICATIONS

The market for space-conditioning systems is extremely diverse and complex. These are fundamentally support systems that are employed to contribute to the functional performance of the buildings in which they are installed. Space-conditioning systems vary greatly with building type and application. The degree of importance attached to space-conditioning systems is heavily influenced by their level of contribution to the building's functional performance. This degree of importance has ramifications for the requirements that the system must fulfill and the criteria utilized to select particular system approaches and technologies.

The market for space-conditioning systems is thus defined by basic external factors, such as economic growth, interest rates, and construction activity, market characteristics, and the availability of particular space-conditioning products or systems.

2.1 Factors Affecting Market Potential and Market Penetration

The key issues in determining the market potential and market penetration for a particular product concept are the degree to which that product concept satisfies the market's requirements, and the effectiveness of the manufacturer's market development program. These key issues include the following:

- External factors and market characteristics define the market requirements that the product concept must address. External factors influence the level and type of building construction required to support the economy, and market characteristics define the specific building configurations and space-conditioning requirements.
- The market potential and market penetration for specific product concepts are defined within the context of the range of market requirements. This process involves the successive determination of the available market, the potential, and, finally, the potential market penetration (or sales potential).
 1. The available market represents a given or specifically defined functional market, i.e., both heating and cooling required. The available market is primarily influenced by external factors and market characteristics.
 2. The market potential represents a portion of an available market that could be served by a particular product concept, i.e., technology. The market potential is primarily influenced by market characteristics and product characteristics.
 3. The market penetration (or sales) potential represents the portion of a potential market that is (or is likely to be) actually realized by a specific product concept. The penetration potential is primarily influenced by market characteristics and product marketing activities.

2.2 The ICES and HAHP-ICES Product Concepts

The ICES product concept is defined as the use of a central plant to meet the heating and cooling requirements of a "community" of buildings. The HAHP-ICES product concept is defined as the use of a heat-actuated heat-pump system in the ICES context. There are, therefore, the following two potentials to be addressed: 1) the market potential for the ICES concept, and 2) the market potential for HAHP-ICES. While some existing buildings may be suitable as ICES applications, new construction is believed to be a more feasible application.

2.3 Base Case

The community of buildings chosen for the ICES was based on the selection of a combination of energy loads that would fit the characteristics of the HAHP. The rationale was to base load the HAHP to achieve a maximum amount of energy savings, leaving certain highly variable loads to be served by conventional means. This led to the selection of a central office building associated with an appropriate number of residential buildings having complementary load characteristics. The base case consisted of one six-story office building of 59,000 square feet and five two-story residential apartment buildings, each building having 24 dwelling units.

The market attractions of this community configuration are discussed in the following sections.

2.4 Base-Case Considerations in Market Potential

2.4.1 Energy Conservation

The analysis of Section 3 projects substantial energy savings from the HAHP-ICES compared with conventional HVAC systems. Energy conservation may have some value in its own right, particularly in community developments having large public exposure, where its publicity value and innovative features may translate into indirect economic benefits. However, this by itself is not a strong factor favoring the selection of the HAHP-ICES in the marketplace. In Section 4, the expected energy savings are translated into dollar savings. The projected dollar savings appear to justify the market potential projections provided in this section as described below.

2.4.2 Cost Advantages

The economic analysis discussed in Section 4 identifies the amount of cost savings of the HAHP-ICES central plant with the term PV_{ds} , which is defined as the amount of money that would be available to defray the additional cost of the energy distribution system needed to transport energy from a central plant to the various buildings located in the system complex. The additional expenses for distribution should be added to the cost of the HAHP-ICES in comparing it with a conventional energy system. A system surplus greater than that cost indicates a favorable situation for the HAHP-ICES. The portion of the system surplus, or net saving (NS), after the total cost of the distribution system has been included can either accrue to the HAHP-ICES thermal utility as a greater return on investment, or be returned to the residential and office owners in

the form of "savings" on their annual thermal energy charges paid to the HAHP-ICES thermal utility. The latter case will be assumed throughout this analysis. For example, the PV_{ds} for the base-case system was estimated in Section 4 to be \$31,585. Thus, on a present value basis, no more than \$31,585 can be spent for the investment in, and the operating and maintenance of, the distribution system if the return requirements of the HAHP-ICES thermal utility are to be satisfied.

To assess the potential market for the HAHP-ICES, it is necessary to have an understanding of how this savings is affected by various parameters. The parametric analysis described in Section 4 shows that the cost advantage of the HAHP-ICES tends to increase with decreased capital costs, particularly for the HAHP-ICES itself. More significant is the increase in savings shown for increased energy costs relative to inflation.

Additional analysis was done to determine the effect of increasing or decreasing the number of residential buildings tied to the central office building. The results of that analysis are shown in Table 2.1.

Table 2.1. PRESENT VALUE SAVINGS VS. RESIDENTIAL/OFFICE BUILDING RATIO^a

Residential/ Office Building	Floor Space Ratio ^b	PV_{ds}^c	Net Saving ^d	Energy Saving,% ^e
2	0.91	(49,339)	--	28.1
5 ^f	2.28	+31,586	(13,414)	32.8
8	3.64	102,000	36,736	32.7
11	5.01	182,523	97,523	--
18	8.20	403,568	272,000	29.9

^a Central plant capital costs were changed for each case to reflect the auxiliary boiler size requirement as the thermal load varied from the base case. Values include pumping requirements but do not include thermal losses. The estimated losses for the base case would increase primary energy consumption about 4%.

^b Floor space ratio = (No. of residential buildings)(Floor space of single residential building)/(Floor space of single office building); floor space of single residential building = 26,880 ft², floor space of office building = 59,000 ft².

^c Dollars available for thermal distribution system.

^d Net Saving = PV_{ds} - Distribution Cost. (Distribution costs were assumed to increase from the base case of \$45,000 for 5 residential buildings by the factor: $\left(\frac{\text{No. of Residential Buildings}}{5}\right)^{0.8}$)

^e Based on primary energy consumption, efficiency of electricity production transmission and distribution: 29.68%. Efficiency of gas distribution: 95%.

^f Base case.

It is apparent that the base case, while representing a nearly optimum configuration of buildings from the energy conservation viewpoint, does not represent the most economical configuration. However, even though the cost savings increase with additional residential buildings, the energy savings appear to be much less sensitive to variation in building ratio. Thus, from the viewpoint of energy conservation, the number of residential buildings associated with each office structure is not critical.

An analysis was also performed, examining the effect of different geographical locations, representing both a range and different combinations of heating-degree-days and cooling-degree-days. (See Section 4 for more complete discussion.) The results showed that locations with a higher number of heating-degree-days resulted in improved economics while locations with fewer heating-degree-days, or conversely, more cooling-degree-days, resulted in less favorable economics. Table 2.2 shows the results of this analysis.

Table 2.2. IMPACT OF GEOGRAPHICAL REGIONS

<u>Location</u>	<u>Heating-Degree-Days</u>	<u>Cooling-Degree-Days</u>	<u>PV_{ds}, *</u> \$
Atlanta	2827	1712	15,404
Kansas City	4812	1609	20,440
Chicago (Base Case)	6506	810	31,586
Minneapolis	7997	674	46,598

* Dollars available for thermal distribution systems. Includes pumping requirements, does not include effects of distribution losses.

2.4.3 Community Configurations for Different Locations

The above considerations reveal considerable flexibility in selecting a suitable number of residential buildings to be attached to the central office building. This permits acceptable installations even in relatively warm climates such as Atlanta.

Relative to the base case, the analysis presented in Section 6, "Potential Growth," indicates that increasing the heating and DHW load via the addition of more residential units improves the economics of the system substantially, while the energy savings potential is only slightly reduced due to increased use of the conventional auxiliary boiler. Thus, it appears that the cooling and heating loads of the base case represent a lower limit in terms of their level and relative ratio. This point is also substantiated by the analysis of the HAHPICES relative to climatic location.

In the climatic location analysis, the office cooling load was held constant in terms of its peak by adjusting the building size, while the total cooling and heating loads were allowed to remain as functions of the climatic location. This sizing of the office building served to maintain central plant equipment requirements with the exception of the auxiliary boiler, which was resized to meet peak thermal demand for each climatic location examined.

The results of this climatic location analysis showed that as the heating load increased relative to the cooling load, the economic viability of the HAHP-ICES improved. Thus, it appears that while warmer climatic locations will improve the cooling load factor of the central plant, the community served must also have high heating loads, possibly as DHW loads, for the system to be viable. An examination of the load data indicates that for the warmer climates such as in Atlanta, Georgia, a community of one office building and eleven or more low-rise residential buildings would be an economically viable community to be served by a HAHP-ICES.

This is shown in Table 2.3 where the relative advantages of the HAHP system over a conventional HVAC system are rated according to the potential net saving (NS) for a number of variations of ICES configurations in each of the geographical regions examined.

Table 2.3. MATRIX OF FEASIBLE LOCATIONS

Residential/Office Building Ratio	Floor Space Ratio*	Location			
		Minneapolis	Chicago	Kansas City	Atlanta
2	0.91	0**	0	0	0
5	2.28	1	0	0	0
8	3.64	2	2	1	0
11	5.01	3	3	2	1
18	8.20	4	4	3	2
Heat Degree Days =		11.9	8.0	3.0	1.6
Cool Degree Days =					

*

Floor space ratio = (No. of residential buildings)(Floor space of single residential building)/(Floor space of single office building); floor space of single residential building = 26,880 ft², floor space of office building = 59,000 ft².

**

0 = Unattractive
1 = Marginal
2 = Favorable
3 = Attractive
4 = Very Attractive

Thus, when more residential buildings can be included (compared with the base case), the ICES can be made attractive in warmer climates. Moreover, normal community growth requiring additional residential buildings will improve the economics of the HAHP relative to the conventional system.

It should be noted that this flexibility of load is possible only within an ICES. A single building does not have it because it is dedicated to a single purpose, and generates energy loads characteristic of that purpose only.

2.4.4 Spatial Arrangement of ICES Components

An additional variable not thoroughly explored is the spatial arrangement of the ICES buildings. Table 2.3 was compiled assuming the distribution cost to vary as described in Table 2.1, Footnote D. For the base-case community of five low-rise residential buildings and one office building, the "tree-like" distribution system assumed (having a 400-foot trunk connecting the office building and central plant to the residential complex, see Sections 4.4.5 and 9.6.5.1) is more or less at the lower limit of the load density necessary for the economic viability of the HAHP-ICES concept. Other community configurations, such as the radial placement of the residential buildings about the office building or a community having a reduced number but larger residential buildings, could result in a denser community with a lower cost distribution system. This would improve the economic viability of the HAHP-ICES.

2.5 Market Potential for the HAHP-ICES

The preceding section established that an HAHP installed in an ICES of the configuration selected offers economies both in energy use and cost compared to a conventional system. It is still necessary to determine how many opportunities may develop for the application of such systems.

2.5.1 ICES Markets

The major uncertainty in projecting the market potential for HAHP-ICES is the market acceptance of the ICES concept itself. ICES-type communities which have been built in the past, such as at Reston, Virginia, Columbia, Maryland, and Allegheny Center in Pittsburgh, Pennsylvania; were not conceived as energy conservation devices, nor have they been built in very large numbers. In order for a significant number of ICES to be built, it will be necessary to offer some significant incentive not present in today's markets.

There has been much speculation and study of fiscal devices that might encourage energy conservation and the adoption of more energy-efficient systems. Very few of them require an ICES for their implementation — those that do must provide sufficient attraction to justify the ICES. Otherwise, the creation of an ICES must depend upon other factors independent of the energy requirements, although energy conservation may add to those factors.

Aside from energy considerations, we see no economic or social trends that would lead to increased community planning of any significant amount. Energy considerations do not yet appear to offer decisive reasons for resorting to community systems as a conservation device. We cannot predict whether changes in tax laws, energy regulations, and financing techniques will make them popular on their own merits.

Economic savings due to the HAHP in an ICES may not be sufficient to justify the ICES in the absence of other incentives, although calculations do indicate a 15% ROI. There may be other incentives, however. An energy utility may see the ICES as an instrument for developing its business and may seek to organize such communities for that purpose. The scope of this study, however, precludes any detailed investigation of this and other alternatives. Rather

than attempt to forecast how attractive an investment vehicle the ICES concept should be, in comparison with other systems, we can use demographic and housing projections to project the market potential for residential/commercial developments. With this market potential as the upper limit, we can develop bracketing scenarios and apply statistics to suggest possible market penetrations for HAHP-ICES under the different scenarios.

2.5.2 Market Study Methodology

The methodology for estimating the market potential for an HAHP-ICES is somewhat complicated by the fact that there is no test market information, no good market analog available, and no fixed size has been established. This means that the usual marketing approach used to forecast markets for consumer durables (radio, television, air conditioner, etc.) must be modified to fit the situation at hand.

Although no fixed size has been established, the minimum ratio of residential/commercial units required to provide a 15% ROI has been determined for the different climatic regions. These ratios are shown in Tables 2.1 and 2.3, and indicate that a larger residential/office ratio is required to achieve a 15% ROI in warmer climates than in colder climates. This shows that the minimum size of the HAHP-ICES is regionally-dependent and indicates that any market study should take this into account.

The use of housing projections for the HAHP-ICES market study should be consistent with projections for both office and multi-family residential construction. As indicated in Table 2.4, the floor area ratio for projected new construction of multi-family residential versus office buildings is not appreciably different from the floor area ratio (2.28) used for the base case. Although this ratio increases in warmer climates (Table 2.3), the correspondence with projected construction is still sufficiently valid to warrant the use of housing projections as the basis for projecting HAHP-ICES market potential. It merely suggests that a smaller proportion of projected office buildings would be candidates for HAHP-ICES developments in warmer climates.

Once the minimum size of the residential components for each region is established, the market study methodology can be developed as a specialized form of a residential housing development market study. The first step is to determine the housing needs of the individual states, based on projected population growth, projected family size, housing replacement requirements, and other demographic factors. By applying a housing-type preference factor to the projected housing needs of individual states, the number of multi-family dwelling units projected to be built in individual states (in contrast to single-family units) during the next decade can be estimated. The same calculations can also be made for the major metropolitan areas of the country.

At this point, the number of apartments to be built in individual states and metropolitan areas has been estimated, but this cannot be used to estimate how many apartment complexes of the size required for a HAHP-ICES might be built, or where. To arrive at this estimate, certain generalizations or assumptions are used: 1) the housing needs of a community will be met by new construction required to provide for new household growth and the replacement of dwellings that have been removed by fire, razing, etc., 2) the present ratio of single-

Table 2.4. PROJECTED MARKET SHARES OF
NEW BUILDING CONSTRUCTION — 1980^{1,2}

	<u>Northeast</u>	<u>Midwest</u>	<u>South</u>	<u>West</u>	<u>Total</u>
Total Building Construction \$10 ⁶	19,641	22,995	35,966	24,048	102,650
Area, in 10 ⁶ -ft ²	601	722	1268	786	3377
Share of Total Area, %	18	21	38	23	100
	<u>Area Share, %</u>				
Residential (Total)	58	55	63	60	60
Housekeeping	56	53	61	57	57
Single Family	39	39	45	39	41
Two Family	1	1	1	2	1
Apartments	15	13	15	17	15
Non-Housekeeping	2	2	2	3	2
Hotels and Motels	2	2	2	2	2
Dorms and Other	< 1	< 1	< 1	< 1	< 1
Non-Residential (Total)	42	45	37	40	40
Commercial and Industrial	29	31	25	28	28
Office and Bank	8	5	5	6	6
Stores and Other	12	14	12	13	13
Manufacturing	9	12	8	8	9
Institutional and Other	13	14	12	12	13
Education and Science	4	4	3	4	4
Hospital and Other	3	3	2	1	2
Public	2	2	2	1	2
Religious	1	1	1	< 1	1
Amusement and Recreation	2	2	2	1	2
Miscellaneous	2	2	2	3	2

family/multi-family dwelling units will be maintained, and 3) a HAHP-ICES development will be built only in cities whose projected new apartment needs are equal to the residential portion of the minimum-sized HAHP-ICES for that geographic region. These generalizations can be put into mathematical form and used to calculate a "Minimum Population Required" factor (MPR) for each state, which is the minimum-sized city in each state that could support a HAHP-ICES development, based on projected population growth, housing removal rate, climate, and housing-type preference. Any city whose population is less than the MPR for the state is not a candidate for a HAHP-ICES development; consequently, approximately 25,000 towns and cities in the United States must be considered and each of them with a population lower than the MPR for its state is eliminated. (This screening eliminated all but about 90 cities and major metropolitan areas as candidates for HAHP-ICES developments.)

It would be quite simple at this point to determine the market potential by simply dividing the population of each of the candidate cities by the MPR for the respective states and total them. However, we must recognize that a HAHP-ICES development can be much larger than the minimum sizes indicated for each climatic region, as evidenced by the site-specific case for Monroeville, Pennsylvania, which is 4.75 times the minimum size calculated for that area. One could, therefore, consider that the HAHP-ICES size range should be between the minimum size calculated for a specific area and a maximum size equal to 4.75 times the minimum size, with the mid-point of 2.375 times the minimum being an appropriate average size. This can now be used to determine the number of HAHP-ICES developments that could be supported by larger cities by simply dividing the population of larger cities by 2.375 times the MPR for the state.

Once the total number of potential HAHP-ICES developments annually has been determined for the country, market penetration projections are made by bracketing with an optimistic and a pessimistic case, as well as two diffusion rate scenarios — slow diffusion and rapid diffusion. The S-shape diffusion curves are drawn and the areas under the curve used to project annual market penetration projections under the different scenarios. These can now be converted to potential energy savings.

2.5.3 Demographic Considerations — General³

In 1970, the official census of the United States indicated a population of approximately 203,212,000 living in 50 states on 3,615,123 sq. miles of land. Nearly 10 years have passed since these numbers were issued and the 1980 census will soon be taken; it is expected to show a population of approximately 221,000,000 based on a projection of the 1970-78 trends. This will represent a 10-year increase of about 8.8%, or an average of slightly less than 1% annually. The projected population for the year 1990 is roughly 242,300,000, an increase over the expected 1980 census of about 9.6% — slightly greater than the growth rate of the 1970's.

The greatest population changes are expected to take place in the western states and, to a lesser extent, the southern states. Table 2.5 gives the projected 1980-1990 population changes for each of the 50 states.

Table 2.5. PROJECTED POPULATION CHANGES³

State	Population		Change, %
	1980	1990	
Alabama	3,840,000	4,200,000	9.4
Alaska	400,000	440,000	10.0
Arizona	2,470,000	3,500,000	41.7
Arkansas	2,260,000	2,600,000	15.0
California	22,950,000	26,000,000	13.3
Colorado	2,770,000	3,500,000	26.4
Connecticut	3,095,000	3,200,000	3.4
Delaware	585,000	630,000	7.7
District of Columbia	670,000	580,000	-13.4
Florida	8,850,000	11,920,000	34.7
Georgia	5,140,000	5,900,000	14.8
Hawaii	900,000	1,100,000	22.2
Idaho	920,000	1,180,000	28.3
Illinois	11,240,000	11,420,000	1.6
Indiana	5,430,000	5,620,000	3.5
Iowa	2,910,000	2,990,000	2.7
Kansas	2,360,000	2,500,000	5.0
Kentucky	3,570,000	3,920,000	9.8
Louisiana	4,040,000	4,450,000	10.1
Maine	1,100,000	1,240,000	12.7
Maryland	4,150,000	4,500,000	8.4
Massachusetts	5,770,000	5,850,000	1.4
Michigan	9,280,000	9,620,000	3.7
Minnesota	4,050,000	4,300,000	6.2
Mississippi	2,430,000	2,680,000	10.3
Missouri	4,960,000	5,110,000	3.0
Montana	820,000	920,000	12.2
Nebraska	1,570,000	1,680,000	7.0
Nevada	720,000	1,000,000	38.9
New Hampshire	900,000	1,100,000	22.2
New Jersey	7,320,000	7,520,000	2.7
New Mexico	1,260,000	1,550,000	23.0
New York	17,400,000	17,090,000	-1.8
North Carolina	5,670,000	6,400,000	12.9
North Dakota	650,000	700,000	7.7
Ohio	10,840,000	10,870,000	.3
Oklahoma	3,000,000	3,400,000	13.3
Oregon	2,520,000	3,040,000	20.6
Pennsylvania	11,680,000	11,690,000	.1
Rhode Island	935,000	910,000	-2.7
South Carolina	3,000,000	3,450,000	15.0
South Dakota	690,000	720,000	4.3
Tennessee	4,460,000	5,000,000	12.1
Texas	13,400,000	16,050,000	19.8
Utah	1,380,000	1,750,000	26.8
Vermont	490,000	550,000	12.2
Virginia	5,175,000	6,000,000	15.9
Washington	3,940,000	4,320,000	9.6
West Virginia	1,860,000	1,970,000	5.9
Wisconsin	4,710,000	5,070,000	7.6
Wyoming	460,000	600,000	30.4
U.S. Total	221,000,000	242,300,000	9.6

The average family, or household size, is projected to drop to 2.7 persons by the year 1980 and to 2.5 persons by the year 1990. This means that the number of households represented by the population projections in the above table will be 81,852,000 in the year 1980 versus 96,920,000, an increase of 15 million households or a percentage increase of 18% over the 10-year period. If we assume that each household occupies a dwelling unit, then we can project an increase of 15 million dwelling units between the years of 1980 to 1990; assuming a 10-year removal rate of 2.75,^{*} which would require an additional 2.5 million replacement units, the total new construction for the United States during the 1980-1990 period would be about 17.5 million dwelling units.

2.5.3.1 Metropolitan Areas in the Year 1990

The population changes in metropolitan areas between the years of 1980 to 1990 will follow roughly the same patterns as the states in which they are located, although this is not true in all instances. For example, the state of California is projected to have a 13.3% population increase, but its largest metropolitan area is projected to experience a small decrease in population. Table 2.6 gives projected population changes for the 50 largest metropolitan areas.

These 50 metropolitan areas will represent a total population of roughly 102 million people in the year 1980 (about 46% of total) and about 109 million (about 45% of total) in the year 1990, or a total growth of only 7 million people between the years 1980 to 1990. Translated into households, or dwelling units, this will represent an increased demand for 5.8 million dwelling units due to population growth in these metropolitan areas. At a 10-year removal rate of 2.75% and a corresponding replacement rate (which would add an additional 1.1 million dwelling units to the demand), a 10-year new construction schedule of 6.9 million dwelling units can be projected for the 50 largest metropolitan areas during the 1980-1990 period.

2.5.4 State-by-State Breakdown of Housing Needs

The projected need for new construction in each state can be determined by using the population projections for the years 1980 to 1990, as shown in Table 2.5 in the year 1990) and housing removal rate (0.275% per year). The new construction needed to supply housing for each state during the years of 1980 to 1990, then, is the sum of the new construction needed for the population growth plus the replacement units to compensate for the removals. This may be expressed by the following mathematical relationship:

$$\begin{aligned} \text{Construction (1980-1990)} &= (D_{1990} - D_{1980}) + 0.00275 \frac{(D_{1990} + D_{1980})}{2} \\ &\quad \text{(growth)} \qquad \qquad \qquad \text{(replacement)} \\ \text{Construction (1980-1990)} &= 1.01375 D_{1990} - 0.98625 D_{1980} \end{aligned}$$

^{*} This is the housing removal rate projected by General Electric⁴ for 1980-1990 and undoubtedly reflects the high proportion of post-World War II housing in existence today, rather than an average lifetime of the buildings.

Table 2.6. PROJECTED POPULATION CHANGES FOR METROPOLITAN AREAS³

	1980 Population	1990 Population	Percent Change		1980 Population	1990 Population	Percent Change
1. New York	9,173,000	8,437,000	-8.0%	26. Ft. Lauderdale- Hollywood, Fla.	980,000	1,550,000	58.2%
2. Chicago	7,032,000	7,087,000	.8%	27. San Jose	1,280,000	1,539,000	20.2%
3. Los Angeles-Long Beach	7,027,000	7,012,000	-.2%	28. Milwaukee	1,435,000	1,467,000	2.2%
4. Philadelphia	4,782,000	4,741,000	-.9%	29. Seattle	1,428,000	1,432,000	.3%
5. Detroit	4,346,000	4,258,000	-2.0%	30. Cincinnati	1,371,000	1,355,000	-1.2%
6. Boston	3,917,000	3,986,000	1.8%	31. Portland, Oreg.	1,168,000	1,355,000	16.0%
7. Houston	2,740,000	3,754,000	37.0%	32. Kansas City	1,301,000	1,328,000	2.1%
8. San Francisco-Oakland	3,210,000	3,314,000	3.2%	33. San Antonio	1,082,000	1,318,000	21.8%
9. Dallas-Fort Worth	2,795,000	3,285,000	17.5%	34. New Orleans	1,168,000	1,303,000	11.6%
10. Washington, D.C.	3,074,000	3,247,000	5.6%	35. Buffalo	1,300,000	1,252,000	-3.7%
11. Nassau-Suffolk, N.Y.	2,740,000	2,937,000	7.2%	36. Columbus, Ohio	1,114,000	1,220,000	9.5%
12. Anaheim-Santa Ana- Garden Grove, Calif.	1,970,000	2,731,000	38.6%	37. Indianapolis	1,158,000	1,203,000	4.1%
13. San Diego	1,826,000	2,455,000	34.4%	38. Sacramento	982,000	1,200,000	22.2%
14. Atlanta	1,930,000	2,334,000	20.9%	39. Hartford-New Britain- Bristol, Conn.	1,058,000	1,082,000	2.3%
15. St. Louis	2,368,000	2,326,000	-1.8%	40. Salt Lake City-Ogden	871,000	1,076,000	23.5%
16. Baltimore	2,176,000	2,287,000	5.1%	41. Memphis	907,000	987,000	8.8%
17. Minneapolis-St. Paul	2,065,000	2,170,000	5.1%	42. Rochester	974,000	986,000	1.2%
18. Pittsburgh	2,255,000	2,118,000	-6.1%	43. Orlando	657,000	951,000	44.7%
19. Tampa-St. Petersburg	1,511,000	2,097,000	38.8%	44. Norfolk-Virginia Beach	831,000	942,000	13.4%
20. Phoenix	1,381,000	1,964,000	42.2%	45. Nashville	803,000	922,000	14.8%
21. Denver-Boulder	1,560,000	1,963,000	25.8%	46. Honolulu	762,000	921,000	20.9%
22. Newark	1,937,000	1,823,000	-5.9%	47. Louisville	889,000	911,000	2.5%
23. Miami	1,513,000	1,806,000	19.4%	48. Oklahoma City	797,000	908,000	13.9%
24. Cleveland	1,908,000	1,764,000	-7.5%	49. Birmingham	820,000	877,000	7.0%
25. Riverside-San Bernardino-Ontario, Calif.	1,375,000	1,659,000	20.7%	50. Greensboro-Winston- Salem-High Point, N.C.	794,000	870,000	9.6%

where —

D_{1980} and D_{1990} = the projected numbers of household units needed for each state in the years 1980 and 1990, obtained by dividing the projected 1980 population by the projected family size of 2.7 persons per family and the projected 1990 population by 2.5 persons per family.

The projected numbers of in-place dwelling units for each state in the years 1980 and 1990 are shown in Table 2.7, together with the projected new construction for each state during the 10-year period, expressed in millions of dwelling units.

2.5.4.1 Breakdown of Housing Types⁵

Attempts to predict trends in housing types have not been particularly successful in recent years. The increased trend to multi-family dwellings from the mid-1960's to the early 1970's was apparently not the major change that it was thought to be, because the trend reversed itself in the mid-1970's. Availability of prime residential building sizes, or lack thereof, did not prove to be the deterrent to single-family dwelling construction that had been predicted. Builders and home-buyers simply traveled farther to find appropriate residential building sites, rather than discard the American dream of owning one's own home.

Table 2.7. STATE-BY-STATE HOUSING NEEDS,
MILLIONS OF DWELLING UNITS

State	D ₁₉₈₀	D ₁₉₉₀	New* Construction
Alabama	1.422	1.680	.301
Alaska	.148	.176	.032
Arizona	.915	1.400	.517
Arkansas	.837	1.040	.229
California	8.500	10.400	2.160
Colorado	1.026	1.400	.407
Connecticut	1.146	1.280	.167
Delaware	.217	.252	.041
District of Columbia	.248	.232	.009
Florida	3.278	4.768	1.601
Georgia	1.904	2.360	.515
Hawaii	.333	.440	.118
Idaho	.340	.472	.142
Illinois	4.163	4.568	.525
Indiana	2.011	2.248	.296
Iowa	1.078	1.196	.149
Kansas	.881	1.000	.144
Kentucky	1.322	1.568	.286
Louisiana	1.496	1.780	.329
Maine	.407	.496	.101
Maryland	1.537	1.800	.309
Massachusetts	2.137	2.340	.265
Michigan	3.437	3.848	.511
Minnesota	1.500	1.720	.264
Mississippi	.900	1.072	.199
Missouri	1.837	2.040	.260
Montana	.304	.368	.073
Nebraska	.580	.672	.108
Nevada	.267	.400	.142
New Hampshire	.333	.440	.118
New Jersey	2.710	3.008	.376
New Mexico	.467	.620	.168
New York	6.444	6.836	.575
North Carolina	2.100	2.560	.524
North Dakota	.241	.280	.046
Ohio	4.015	4.348	.498
Oklahoma	1.111	1.360	.283
Oregon	.933	1.216	.312
Pennsylvania	4.326	4.676	.474
Rhode Island	.346	.364	.028
South Carolina	1.111	1.380	.303
South Dakota	.256	.288	.040
Tennessee	1.652	2.000	.398
Texas	4.963	6.420	1.614
Utah	.540	.700	.206
Vermont	.181	.220	.044
Virginia	1.917	2.400	.542
Washington	1.459	1.728	.313
West Virginia	.689	.788	.119
Wisconsin	1.766	2.088	.336
Wyoming	.170	.240	.076
U.S. Total			17.703

*New Construction = $1.01375D_{1990} - .98625D_{1980}$

In a similar manner, the rapidly escalating cost of new houses has not proven to be a major deterrent to house buying because potential home buyers have regarded home ownership as almost the only way for the average person to combat the effects of inflation. Cost and availability of mortgage money has always been only a temporary deterrent to home buying, since this factor is tied so closely to the business cycle. Consequently, the percentage of single-family homes in the nation's housing mix during the next 10 years will probably continue to remain at the 65 to 70% level, overall, distributed approximately according to the 1970 mix as shown in Figure 2.1. This pattern indicates a greater trend toward multi-family dwellings in the more heavily populated areas of the Northeast and West Coast, and a particular dominance of single-family dwellings in the less populated areas of the country.

2.5.5 Potential Markets

The potential market for the heat-actuated heat pump ICES may be estimated by utilizing some of the results of this study's sensitivity analyses, applying them to some of the demographic projections, and applying elementary marketing statistics. For example, Table 2.1 indicates that a 15% return for the base case can be realized by a residential/office (R/O) building ratio between 5 (net saving - \$13,414) and 8 (net saving = +\$36,736), and a simple plot of these data shows that the 15% return is realized at an R/O ratio of 6. At 24 dwelling units per residential building, the number of residential dwelling units for this ratio is 6 X 24, or 144 dwelling units; this is the minimum sized development to achieve a 15% return in a city of a base case community.

The effect of climate, or more precisely, the ratio of annual heating degree days to annual cooling degree days (HDD/CDD) is shown in the matrix of feasible locations, Table 2.3. (These data may also be plotted to determine intermediate values of extrapolate beyond HDD/CDD values of 11.9 and 1.6.) Translated into minimum-sized developments to achieve a 15% return in various geographic, or climatic, regions, these data indicate that the following feasibility criteria (Table 2.8) should apply to the different locations:

Table 2.8. MINIMUM-SIZED DEVELOPMENTS FOR 15% ROI

<u>HDD/CDD</u>	<u>R/O</u>	<u>Dwelling Units</u>	<u>Required Population Increase</u>		
			<u>1980</u>	<u>1985</u>	<u>1990</u>
11.9	5	120	324	312	300
8.0	6	144	388	374	360
3.0	8	160	432	416	400
1.6	11	264	712	686	660

Figure 2.1. PERCENTAGE OF SINGLE-FAMILY DETACHED DWELLINGS, 1970

The last 3 columns in this table indicate the number of people expected to occupy the indicated dwelling units at the projected family sizes of 2.7 (1980), 2.6 (1985), and 2.5 (1990). These are very significant numbers because they are part of the rationale for the projected market potential methodology, which may be summarized as follows:

1. As indicated by the HAHP-ICES base case design, the occupants of the dwelling units will be apartment dwellers whose housing needs result from the net population growth of the community.
2. The required population increases indicated in Table 2.8 are for apartment dwellers only and are 25% to 50% of the gross population growth, depending on the multi-family portion of the housing mix. The total population growth of the community required to support such a development, therefore, is at least the values in Table 2.8 divided by 0.25 - 0.50, and generally 0.30 to 0.35. Obviously, this will depend on the housing mix of the community, such as was indicated earlier (see Figure 2.1). Larger cities, especially in the northeastern United States and California, will have a relatively higher proportion of apartment dwellers compared with the rest of the United States and will not require as large an overall population growth to support such an ICES development as would those areas with larger proportions of single-family homes. However, these are also the areas of lowest projected population growth.
3. The community size that would be needed to support a HAHP-ICES development is calculated by first determining the minimum-sized development required by climatic considerations (i.e., from the HDD/CDD ratio and the number of residential units shown in Table 2.8; 120, 144, 160, or 264), multiplying by the appropriate household size, and dividing by the annual new housing requirements of the community (i.e., annual population growth plus annual housing removal rate). This is expressed mathematically as -

$$P = \frac{N \cdot H}{(G + R)(1 - S_f)}$$

where -

- P = minimum population required (MPR)
- N = minimum number of dwelling units for a given HDD/CDD ratio (Table 2.8)
- H = household size (2.7 in 1980; 2.5 in 1990)
- G = annual population growth rate
- R = annual housing removal rate
- S_f = fraction of single-family dwellings in housing mix.

A minimum population requirement is then calculated for each state, using the state population growth rates indicated in Table 2.5. These values are shown in Table 2.9.

4. These values are now used to rank the 50 states with respect to market potential for HAHP-ICES and to determine which cities in the various states are large enough to support a base-case type development. The most promising states are those with the smallest minimum population required to support such a development, as indicated by the numbers in Table 2.9. The most promising states for such a development are the

Table 2.9. STATE-BY-STATE MINIMUM POPULATION REQUIRED (MPR)
TO SUPPORT HAHP-ICES

State	MPR	State	MPR
Alabama	161,400*	Missouri	206,643
Alaska	70,000	Montana	59,652
Arizona	--	Nebraska	109,600
Arkansas	110,445	Nevada	39,952
California	122,000S	New Hampshire	35,728
California	66,579N	New Jersey	152,660
Colorado	37,000	New Mexico	46,143*
Connecticut	101,463	New York	656,800
Delaware	79,617	North Carolina	125,265
District of Columbia	--	North Dakota	85,339
Florida	--	Ohio	350,360
Georgia	111,703*	Oklahoma	122,000
Hawaii	--	Oregon	44,540
Idaho	40,193	Pennsylvania	375,000
Illinois	245,655	Rhode Island	--
Indiana	171,000	South Carolina	128,900
Iowa	196,073	South Dakota	147,500
Kansas	153,316	Tennessee	80,900
Kentucky	94,677	Texas	86,935*
Louisiana	152,560*	Utah	36,200
Maine	50,485	Vermont	59,627
Maryland	95,838	Virginia	63,710
Massachusetts	187,951	Washington	72,210
Michigan	165,674	West Virginia	137,364
Minnesota	99,642	Wisconsin	100,483
Mississippi	150,000*	Wyoming	31,382

* Northern portion only.

N = northern California.

S = southern California.

fastest growing states in the colder climatic areas and the least promising states are those in warm climates and those with least population growth potential. Unfortunately, the most promising states are also the least populated states, so they do not represent a large market penetration. The most promising states are those with minimum population requirements (MPR) of approximately 35,000 to 50,000 and include:

Wyoming	Colorado	New Mexico (northern part only)
Utah	Idaho	Oregon
New Hampshire	Nevada	Maine

This group represents a little over 11 million population, or about 5% of the United States. The next most promising states have minimum population requirements of 50,000 to 100,000 and include:

California (northern part only)	Washington
Alaska	Vermont
Delaware	Virginia
Montana	Tennessee
Texas (northern part only)	North Dakota
Maryland	Kentucky
Minnesota	

The least promising states, for which little market penetration appears likely, are:

Arizona	Texas (southern part only)
Florida	Louisiana (southern part only)
Hawaii	Mississippi (southern part)
Rhode Island	Alabama (southern part)

5. The total market potential is given by the total number of cities that meet the minimum population requirements in their respective states, multiplied by the number of HAHP-ICES developments that could be supported by the growth of the city.* This latter factor is rather arbitrary since there is no maximum size for the HAHP-ICES. The minimum size has been determined by the sizes required to produce a 15% return in each of 4 climatic regions; however, a larger development such as the site-specific Monroeville project could also be considered as a viable option. With no other size limitation to go on, our market potential projections will be based on a size that falls between the minimum size and the size of the site-specific case. The Monroeville project involves 42 townhouses, 5 low-rise apartment buildings containing 24 units per building, and 5 high-rise buildings containing 104 units per building; this is equal to a total of 682 residential dwelling units (or 4.75 times the base case number of 144) to complement the 259,000 ft² of office and retail space. This analysis, then, will use a variable market element size ranging from the minimum size for each HDD/CDD region to a size that is 4.75 times this minimum value, as shown in Table 2.10. Corresponding population values range from the MPR values in Table 2.9 to 4.75 times these values.

* The 50 largest metropolitan areas are treated separately, since their growth rates may differ from those of the states in which they are located. Table 2.11 gives the projected new construction to satisfy housing needs for these metropolitan areas.

Table 2.10. MARKET ELEMENT SIZES FOR HDD/CDD REGIONS

<u>HDD/CDD</u>	<u>Market Element Dwelling Units</u>	<u>Minimum Population Range</u>
11.9	120 - 568	Lower bound is the MPR value for each state (from Table 2.9). Upper bound is equal to 4.75 times the MPR value, and size used for market study is 1/2 this value, or 2.375 times MPR.
8.0	144 - 682	
3.0	160 - 758	
1.6	264 - 1251	

The rationale for using a variable market element may be explained as follows: If a minimum population of 50,000 is required to support a single base-case HAHP-ICES involving 144 dwelling units, a city of 100,000 population would simply involve a larger HAHP-ICES of 288 dwelling units rather than two developments of 144 dwelling units each. Obviously, many other factors would be involved in any real-world situation — land availability, availability of capital funds, real estate market, etc. — but this appears to be a valid assumption for projecting potential markets for the variable-sized HAHP-ICES. An arbitrary assumption has been made that a logical market element size should lie approximately half-way between the upper and lower bounds, or 2.375 MPR.

6. The market potential is now constructed for each state, based on the cities that fall within the MPR range for the state. These values are shown in Table 2.12, which indicates the cities in which at least one HAHP-ICES could be supported by housing needs. For larger cities, market potential is based on 2.375 MPR.
7. The total annual market potential for HAHP-ICES is 390 developments, ranging in size from the minimum base-case size to 1/2 the size used for the Monroeville site-specific case. The rate at which this potential market can be penetrated cannot be assessed with any degree of confidence, since this depends on so many unknown or unpredictable factors. However, we can make some generalizations that should be reasonably valid:
 - Market penetration will probably follow some type of S-shaped diffusion curve, even though this type of market penetration pattern is historically associated with consumer products rather than such large capital-intensive projects as HAHP-ICES.
 - The upper limit of the market potential (390 developments per year) is based on the entire annual potential market for multi-family dwelling units in the cities deemed capable of supporting HAHP-ICES, by virtue of population growth, size, climate, and housing type. It is inconceivable that the entire value of this potential market could be captured in any city or metropolitan area, because this would mean that all new apartment buildings would be constructed as part of a HAHP-ICES development. Such factors as availability of suitably large tracts of land, zoning restrictions, capital availability, etc., would mitigate against such an eventuality occurring, and a more realistic approach to predicting markets would be to select an optimistic and a pessimistic percentage of this potential that could be

Table 2.11. HOUSING NEEDS FOR 50 LARGEST METROPOLITAN
AREAS, MILLIONS OF DWELLING UNITS

Metropolitan Area.	D ₁₉₈₀	D ₁₉₉₀	New* Construction
New York	3.397	3.374	.070
Chicago	2.604	2.834	.305
Los Angeles-Long Beach	2.603	2.805	.276
Philadelphia	1.771	1.896	.175
Detroit	1.610	1.703	.139
Boston	1.451	1.594	.185
Houston	1.015	1.502	.522
San Francisco-Oakland	1.189	1.326	.172
Dallas-Ft. Worth	1.035	1.314	.311
Washington, D.C.	1.139	1.299	.194
Nassau-Suffolk, N.Y.	1.015	1.175	.190
Anaheim-Santa Ana- Garden Grove, Calif.	.730	1.092	.387
San Diego	.676	.902	.329
Atlanta	.715	.934	.242
St. Louis	.877	.930	.078
Baltimore	.806	.915	.133
Minneapolis-St. Paul	.765	.868	.126
Pittsburgh	.835	.847	.035
Tampa-St. Petersburg	.560	.839	.298
Phoenix	.511	.786	.293
Denver-Boulder	.578	.785	.226
Newark	.717	.729	.032
Miami	.560	.722	.180
Cleveland	.707	.706	.018
Riverside-San Bernardino- Ontario, Calif.	.509	.664	.171
Ft. Lauderdale- Hollywood, Fla.	.363	.620	.271
San Jose	.474	.616	.157
Milwaukee	.531	.587	.071
Seattle	.529	.573	.061
Cincinnati	.508	.542	.048
Portland, Ore.	.433	.542	.122
Kansas City	.482	.531	.063
San Antonio	.401	.527	.139
New Orleans	.432	.521	.102
Buffalo	.481	.501	.034
Columbus, Ohio	.413	.488	.087
Indianapolis	.428	.481	.066
Sacramento	.364	.480	.128
Hartford-New Britain- Bristol, Conn.	.392	.433	.052
Salt Lake City-Ogden	.322	.430	.118
Memphis	.336	.395	.069
Rochester	.361	.394	.043
Orlando	.243	.380	.146
Norfolk-Virginia Beach	.308	.377	.078
Nashville	.297	.369	.081
Honolulu	.282	.368	.095
Louisville	.329	.364	.045
Oklahoma City	.295	.363	.077
Birmingham	.304	.351	.059
Greensboro-Winston- Salem-High Point, N.C.	.294	.348	.063
U.S. Total			7.322

* New Construction = $1.01375D_{1990} - 0.98625D_{1980}$

Table 2.12, Part 1. POTENTIAL MARKET VALUES

State	MPR	Potential Market	Cities (Population)
Alabama	160,000N*	1	Birmingham (300,000)
Alaska	70,000	1	Anchorage (80,000)
Arizona		0	--
Arkansas	110,000	1	Little Rock (149,000)
California	70,000N*	16	Los Angeles (7,027,000)G [†]
	122,000S [†]	16	San Francisco (3,210,000)G [†]
		14	San Jose (1,280,000)G [†]
		8	Sacramento (982,000)
		1	Fresno (166,000)
		1	Stockton (115,000)
Colorado	37,000	2	Boulder (67,000);
			Fort Collins (43,000)
		2	Greeley (39,000);
			Pueblo (97,000)
		18	Denver (1,560,000)G [†]
		2	Colorado Springs (135,000)
Connecticut	100,000	1	Bridgeport (147,000)
		4	Hartford (1,000,000)G [†]
		1	New Haven (128,000)
		1	Waterbury (111,000)
Delaware	80,000	1	Wilmington (80,000)
District of Columbia	--	18	Washington (3,000,000)G [†]
Florida	--	0	--
Georgia	112,000N*	8	Atlanta (1,930,000)G [†]
Hawaii	--	0	--
Idaho	40,000	2	Boise (87,500); Pocatello (40,000)
Illinois	245,000	18	Chicago (7,032,000)G [†]
Indiana	171,000	4	Indianapolis (1,156,000)G [†]
		1	Fort Wayne (181,000)
		1	Gary (186,000)
Iowa	190,000	1	Des Moines (194,000)
Kansas	150,000	4	Kansas City (1,300,000)G [†] ,
			includes Kansas City, Missouri
		1	Wichita (246,000)
Kentucky	95,000	4	Louisville (889,000)G [†]
		1	Lexington (889,000)
Louisiana	155,000N*	1	Shreveport (192,000)
Maine	50,000	1	Portland (65,000)
Maryland	96,000	12	Baltimore (2,176,000)G [†]
Massachusetts	188,000	18	Boston (3,917,000)G [†]
Michigan	166,000	1	Grand Rapids (184,000)
		12	Detroit (4,346,000)G [†]
Minnesota	100,000	10	Minneapolis-St. Paul (2,065,000)G
		1	Duluth (100,578)
Mississippi	155,000N*	1	Jackson (171,000)
Missouri	207,000	8	St. Louis (2,368,000)G [†]
Montana	60,000	1	Billings (61,600)
		1	Great Falls (60,000)

Table 2.12, Part 2. POTENTIAL MARKET VALUES

State	MPR	Potential Market	Cities (Population)
Nebraska	110,000	1	Lincoln (158,500)
		2	Omaha (372,000)
Nevada	40,000	2	Las Vegas (125,300)
		1	Reno (84,000)
New Hampshire	36,000	2	Manchester (89,500)
		1	Nashua (61,800)
New Jersey	153,000	6	Newark (1,937,000)G [†]
New Mexico	46,000N [*]	2	Albuquerque (244,000)
New York	3-600,000	8	New York City (9,173,000)G [†]
		6	Buffalo (1,300,000)G [†]
		4	Rochester (974,000)
		20	Nassau-Suffolk (2,740,000)
North Carolina	125,000	5	Raleigh (122,000); Greens- boro (794,000)G [†] ; Charlotte (281,000)
North Dakota	85,000	0	--
Ohio	350,000	2	Columbus (1,114,000)G [†]
		2	Cincinnati (1,371,000)G [†]
		3	Cleveland (1,908,000)G [†]
		1	Toledo (383,000)
Oklahoma	122,000	2	Oklahoma City (797,000)G [†]
		1	Tulsa (331,600)
Oregon	45,000	1	Salem (68,000)
		1	Eugene (76,000)
		12	Portland (1,168,000)G [†]
Pennsylvania	375,000	14	Philadelphia (4,782,000)G [†]
		4	Pittsburgh (2,255,000)G [†]
Rhode Island		0	--
South Carolina	130,000	0	--
South Dakota	147,500	0	--
Tennessee	80,000	1	Chattanooga (119,000)
		4	Nashville (803,000)G [†]
		1	Knoxville (175,000)
		4	Memphis (907,000)G [†]
Texas	86,935N [*]	2	Amarillo (127,000); Abilene (89,000)
	112,000S [†]	1	Lubbock (149,000)
		11	Dallas-Ft. Worth (2,795,000)G [†]
Utah	36,000	10	Salt Lake City (871,000)G [†]
		1	Provo
Vermont	60,000	0	--
Virginia	64,000	6	Norfolk (831,000)G [†]
		3	Richmond (250,000)
		1	Roanoke (92,000)
Washington	72,000	5	Seattle (1,428,000)G [†]
		2	Spokane (170,000)
West Virginia	137,000	0	--
Wisconsin	100,000	1	Madison (173,000)
		8	Milwaukee (1,435,000)G [†]
Wyoming	31,000	2	Cheyenne (41,000); Casper (39,000)
Total		390	

*N = Northern part of the state only.

†S = Southern part of the state only.

‡G = Greater metropolitan area.

achieved by HAHF-ICES development projects. There are no valid precedents to provide any guidance, so we will simply arbitrarily select some value as being certainly a pessimistic percentage and another as being certainly optimistic. The most pessimistic value would be zero, and this could easily be a valid assumption. However, a 15% ROI would seem to be a reasonable return for some developers, so we will select 1% as a pessimistic value and 25% as being certainly an optimistic value. This suggests that the annual market potential would be somewhere between $400 \times .01$ and $400 \times .25$, or between 4 and 100. Thus, two sets of diffusion curves can be drawn, one with 4 as the upper limit and the other with 100 as the upper limit. (The value of 400 represents a "rounding off" of the 390 potential market value to facilitate calculations. This is within the imprecision of the methodology.)

- Conventional marketing of consumer products finds all potential buyers divided into 5 different groups, based on their relative willingness to try a new product. This may be illustrated by the following historical adoption curve (Figure 2.2) that divides the normal distribution pattern into these five different groups.

Figure 2.2. HISTORICAL ADOPTION CURVE⁵

Based on these percentages, a standard S-shaped diffusion curve can be drawn which shows the form that cumulative market penetration will have, as illustrated in Figure 2.3. Actually, Figure 2.3 shows several possible diffusion curves, each of them based on a different diffusion, or market penetration rate. In projecting market penetration for new consumer products, the slope of the diffusion curve is either estimated from historic penetration patterns for similar products (e.g., television, radio, hybrid corn, etc.), or projected from test market data to establish the early portion of the curve. Neither approach appears applicable, so we will again select arbitrarily a slow diffusion rate curve and a rapid one, and attempt to bracket our projection for HAHF-ICES, using an historically rapid diffusion curve (for consumer goods) of about 8 years and an historically slow diffusion curve of about 35 years. These two curves will then assume the shapes shown in Figure 2.4. The two values selected to bracket the upper

Figure 2.3. HISTORICAL DIFFUSION CURVE⁵

limit of the diffusion curve are 4 and 100 HAHP-ICES per year. These values can now be used in conjunction with the two diffusion curves to estimate a range of projected market penetration values. Annual market penetration can be estimated directly from the area under curves and aggregated in a summary shown in Table 2.13.

It should be recognized that a statistical treatment has very limited applicability when the upper penetration limit is as low as 4 units per year as indicated for the pessimistic case. Nevertheless, on a cumulative basis, the market potential for the entire diffusion period can be estimated to a limited extent by determining the areas under the curves and equating them to market penetration. Table 2.13 shows the estimated annual market penetration values, determined from the areas under the diffusion curves, for both pessimistic and optimistic projections of market acceptance and for both slow and rapid diffusion.

It should also be recognized that the market potential and market penetration estimates apply to the construction of commercial/residential Planned Unit Developments of the size and building mix required to support HAHP-ICES at a 15% ROI, and not uniquely to the HAHP-ICES. In other words, the market estimates could also apply to the same size and type of real estate developments, irrespective of whether they employed a HAHP-ICES or another energy system that satisfied the energy requirements and provided the same financial incentive. This is the reason for establishing a range into which

Figure 2.4. POSSIBLE HAHP-ICES MARKET DIFFUSION CURVES

Table 2.13. ESTIMATED MARKET PENETRATION

Year	Slow Diffusion			Rapid Diffusion	
	<u>Pessimistic</u>	<u>Optimistic</u>		<u>Pessimistic</u>	<u>Optimistic</u>
1980	0	0		0	2
1981	0	1		0	12
1982	0	2		1	25
1983	0	2		2	40
1984	0	4		2	60
1985	0	5		4	80
1986	0	7		4	94
1987	0	9		4	98
1988	1	12	8 yr total	17	411
1989	1	16			
1990	1	18			
1991-1995	6	152			
1996-2000	11	270			
2001-2005	15	378			
2006-2010	18	455			
2011-2015	<u>20</u>	<u>495</u>			
35-yr total	73	1826			

the HAHP-ICES market penetration should fall. Such factors as greater escalation of energy costs and government actions to encourage HAHP-ICES use (e.g., tax incentives, special regulations, etc.) would increase the chances for market penetration.

No attempt has been made to predict the actual HAHP-ICES market penetration that could be expected, but rather to project the market penetration potential associated with each of the 4 hypothesized scenarios, based on idealized S-shape diffusion curves. However, the projections become very useful in relating the energy savings that could be realized if the market penetration potentials were to be achieved.

2.5.6 Potential Energy Savings

The most optimistic case for energy savings among the four scenarios represented in Table 2.12 is the rapid diffusion - optimistic case, which shows that approximately 411 HAHP-ICES developments would be possible by the year 1990 if we assume that the first such development could not realistically be built until the 1982-83 time frame. This would offer the promise of an annual energy savings for the country of 5.2×10^9 Btu/yr (from Table 2.13) for each minimum-sized HAHP-ICES, or, since the 411 developments should be equal in size

to about 711 minimum-sized developments, the total annual energy savings would be $5.2 \times 10^9 \times 710 = 3.7 \times 10^{12}$ Btu. At an energy content of 5.8×10^6 Btu/bbl oil, this is equal to an energy saving of 638,000 bbl of crude oil equivalents per year.

The least optimistic case involves the slow diffusion pessimistic scenario and suggests only about 3 HAHP-ICES developments by the year 1990. This is equal to an energy savings of only about 27×10^9 Btu/yr or 4,657 bbl oil/yr.

We have avoided making any predictions as to when market penetration might occur, other than to suggest some possible scenarios. The numbers given in Table 2.13 should be regarded as estimates of market potential under different market capture assumptions, and not predictions of market capture.

2.6 Institutional Considerations

There are many institutional problems associated with the acceptance of an ICES and these are discussed in other studies.⁶⁻¹² This task is concerned only with those pertaining to the use of the HAHP in an ICES and the impact that it may have on the institutional problems of both.

2.6.1 Environmental Considerations

The environmental impacts discussed in this study assume the use of natural gas although there is no technical reason why an oil-fired HAHP cannot be used. The environmental attractions of using gas are well known. We expect that environmental pollution will be a factor in fuel selection and this will favor the use of natural gas if it is available.

Thus, the availability of natural gas could be a significant factor in the social acceptance of an HAHP where environmental concerns may discourage the use of oil. However, no problems are foreseen that would restrict the long-term availability of natural gas for use in the residential and commercial sectors of the gas market. Since it is unlikely that the use of natural gas in these markets will be restricted for environmental reasons, it follows that environmental problems can be minimized through the use of natural gas.

Some substantiation of this optimistic view of natural gas availability may be in order.

2.6.2 Natural Gas Availability

It has been a policy of the Federal Government to assign the highest priorities for natural gas use to essential residential and commercial uses. Thus, during recent periods of gas shortages, industrial boiler fuel and other easily transferable gas loads have been curtailed in order to preserve the available supplies for residential, commercial, and public need applications.

There have not been any local or temporary shortages of gas supply to high-priority customers. Any possibilities of shutdowns to high-priority customers have been circumvented by transfers of gas from other areas. It does not appear that such shutdowns are likely to occur in the foreseeable future because of the large volumes of industrial gas loads that can be diverted to high-priority use, as alternative fuels, such as coal, are phased into industrial plants.

Several years ago, the Federal Power Commission issued a priority-of-service category listing for use during periods of curtailed deliveries by a transmission company. The priority-of-service categories are the following:

1. Residential, small commercial (less than 50,000 CF on a peak day)
2. Large commercial requirements (50,000 CF on a peak day), firm industrial requirements for plant protection, feedstock and process needs, and pipeline customer storage injection requirements.
3. All industrial requirements not specified in Items 2, 4, 5, 6, 7, 8, or 9.
4. Firm industrial requirements for boiler fuel use at less than 3 million CF/day, but more than 1.5 million CF/day, where alternative fuel capabilities can meet such requirements.
5. Firm industrial requirements for large volume (3 million or more CF/day) boiler fuel use where alternative fuel capabilities can meet such requirements.
6. Interruptible requirements of more than 300,000 CF/day, but less than 1.5 million CF/day, where alternative fuel capabilities can meet such requirements.
7. Interruptible requirements of intermediate volumes (from 1.5 million CF/day through 3 million CF/day), where alternative fuel capabilities can meet such requirements.
8. Interruptible requirements of more than 3 million CF/day, but less than 10 million CF/day, where alternative fuel capabilities can meet such requirements.
9. Interruptible requirements of more than 10 million CF/day, where alternative fuel capabilities can meet such requirements.

The problem is one of political administration of end-use allocation rather than a physical limitation on the availability of natural gas for residential and commercial use.

The Gas Requirements Committee of the gas utility industry has prepared a detailed projection of future gas consumption by state and by category of sales to the year 1985; this projection is presented in Table 2.14. It is apparent that the residential and commercial sectors are projected to consume about 8.62 trillion CF of gas or about 42% of the 20.6 trillion CF total consumption for all uses projected for 1985.

It is currently uncertain if the total gas production in 1985 will equal this projected total consumption. A large number of gas supply projections have been made by various authors. Most projections predict nearly constant or slightly declining gas supply. No projections have been made that predict declines in supply sufficient to encroach upon the 9 trillion CF needed to supply the residential and commercial markets. We can, therefore, conclude that the future natural gas supply will be more than adequate to serve these markets through 1985.

Table 2.14. ESTIMATED GAS CONSUMPTION BY STATE AND CLASS OF SERVICE, 1985
(Million CF at 1000 Btu/CF at 14.73 psia)

	Firm			Electric Utilities for Power Generation		Interruptible		Other	Total Consumption
	Residential	Commercial	Industrial	Firm	Interruptible	Commercial	Industrial		
UNITED STATES TOTAL FIELD USE	5,514,381	2,562,948	4,328,636	1,201,871	336,553	214,727	1,442,554	1,131,247	18,555,917
TOTAL EXCLUDING FIELD USE									1,823,000
									16,732,917
1. NEW ENGLAND	168,900	66,704	37,338	—	3,160	743	4,854	15,317	297,016
Connecticut	35,474	16,630	11,456	—	—	—	—	3,241	66,801
Maine	1,068	679	825	—	—	—	—	200	2,772
Massachusetts	109,216	40,426	19,894	—	3,060	330	3,395	9,964	186,285
New Hampshire	4,642	2,910	1,005	—	—	—	—	374	8,931
Rhode Island	16,925	5,060	4,060	—	—	—	—	1,302	27,347
Vermont	1,575	999	98	—	100	413	1,459	236	4,880
2. APPALACHIAN	1,535,621	633,957	1,023,302	468	2,000	20,992	91,902	193,367	3,501,609
Delaware	9,455	3,490	4,100	—	—	250	754	655	18,704
District of Columbia	13,871	10,196	—	—	—	1,769	238	894	26,968
Kentucky	82,396	24,162	35,516	—	53	1,062	14,919	23,292	181,400
Maryland	75,909	22,776	23,913	—	—	4,411	33,883	10,848	171,740
New Jersey	165,846	79,678	51,447	—	1,030	15	25	14,165	312,406
New York	341,767	133,537	90,120	55	917	6,643	5,024	26,912	604,975
Ohio	439,049	182,221	409,633	13	—	2,985	23,494	29,918	1,087,313
Pennsylvania	302,637	122,390	296,492	400	—	30	2,829	37,775	762,553
Virginia	51,016	30,587	36,659	—	—	3,733	9,069	9,423	140,487
West Virginia	53,675	24,920	75,422	—	—	94	1,667	39,285	195,063
3. SOUTHEAST	334,155	188,720	228,342	49,330	1,750	16,471	117,721	76,614	1,013,103
Alabama	68,061	24,875	62,859	—	—	2,123	39,724	16,631	214,273
Florida	25,046	22,922	5,155	49,330	1,630	3,866	23,166	4,939	136,054
Georgia	114,697	57,542	46,101	—	92	7,113	36,662	17,149	279,356
North Carolina	35,519	28,535	28,973	—	—	—	1,832	8,248	103,107
South Carolina	32,640	12,574	18,506	—	28	3,369	15,279	7,914	90,310
Tennessee	58,192	42,272	66,748	—	—	—	1,058	21,733	190,003
4. GREAT LAKES	1,257,673	616,877	683,586	10,900	8,561	15,543	106,825	92,086	2,792,051
Illinois	546,613	242,598	292,794	1,935	1,990	282	12,757	31,820	1,136,789
Indiana	195,858	73,547	127,764	—	—	721	4,507	18,021	420,418
Michigan	384,448	220,559	224,489	8,965	5,105	3,786	36,717	33,996	918,065
Wisconsin	130,754	80,173	38,539	—	1,466	10,754	52,844	2,249	316,779
5. NORTHERN PLAINS	307,819	147,802	116,599	673	8,190	52,848	30,400	36,225	700,556
Iowa	102,586	47,035	71,218	377	4,768	9,124	11,412	16,310	262,830
Minnesota	124,340	46,109	17,462	296	2,455	28,744	8,383	13,422	241,211
Nebraska	56,538	36,820	27,581	—	937	9,078	8,172	5,272	144,398
North Dakota	11,978	10,592	53	—	30	3,045	1,073	715	27,486
South Dakota	12,377	7,246	285	—	—	2,857	1,360	506	24,631
6. MID-CONTINENT	334,289	155,830	136,801	259,055	23,337	16,907	183,268	106,559	1,216,046
Kansas	97,705	47,329	11,260	3,260	15,037	3,786	21,741	62,171	262,289
Missouri	151,880	60,906	29,009	—	300	7,767	12,509	8,572	270,943
Oklahoma	84,704	47,595	96,532	255,795	8,000	5,354	149,018	35,816	682,814
7. GULF COAST	438,877	296,503	1,840,393	866,659	281,651	22,973	449,312	373,303	4,569,671
Arkansas	48,110	32,350	115,404	13,152	—	—	9,167	22,888	241,071
Louisiana	101,332	28,093	524,954	259,578	68,178	—	31,820	152,449	1,166,804
Mississippi	36,271	23,193	49,012	2,022	4,029	—	20,179	33,278	167,984
Texas	253,164	212,867	1,151,023	591,907	209,444	22,973	388,146	164,688	2,994,212
8. ROCKY MOUNTAIN	235,766	128,305	47,175	3,217	7,830	15,591	39,318	23,623	500,825
Colorado	126,698	84,842	17,126	2,817	7,710	6,850	9,802	7,509	263,354
Montana	23,880	17,440	2,200	400	120	300	18,500	2,722	65,562
Utah	68,639	17,383	5,934	—	—	7,957	2,469	5,222	107,604
Wyoming	16,549	8,640	21,915	—	—	484	8,547	8,170	64,305
9. PACIFIC SOUTHWEST	820,550	275,058	120,265	11,569	74	35,915	350,818	96,980	1,711,229
Arizona	41,436	15,749	5,441	2,983	—	—	—	10,544	76,153
California	719,482	203,595	95,956	3,005	—	35,661	350,743	64,118	1,472,560
Nevada	20,133	13,829	2,505	2,666	—	—	—	733	39,866
New Mexico	39,499	41,885	16,363	2,915	74	254	75	21,585	122,650
10. PACIFIC NORTHWEST	80,731	53,192	94,835	—	—	16,744	68,136	4,588	318,226
Idaho	12,853	9,850	29,667	—	—	540	4,356	189	57,455
Oregon	24,295	15,824	28,859	—	—	333	22,505	1,888	93,704
Washington	43,583	27,518	36,309	—	—	15,871	41,275	2,511	167,067
11. PACIFIC*	—	—	—	—	—	—	—	112,585	112,585
Alaska	—	—	—	—	—	—	—	107,985	107,985
Hawaii	—	—	—	—	—	—	—	4,600	4,600

* Alaska and Hawaii's data and category of use statistics cannot be shown separately without revealing confidential data.

There is less definitive data available on the time period from 1985 to 2000. Some projections, particularly those of the DOE, tend to peak sometime after 1985 and to decline slowly thereafter. Others show fairly constant annual gas production to the year 2000. The uncertainty of future gas production rests not with the existence of gas reserves but with the economics of production relative to other forms of energy. Nevertheless, all of the future projections are so far above the requirements of the residential and commercial markets that as long as current allocation priorities are enforced, we can foresee no shortage of natural gas for any HAHP-ICES. In fact, the availability of natural gas should improve with time as adjustments are made to shift gas consumption away from low priority industrial boiler fuel loads. The current reversal of this trend will be temporary due to the recent change in regulations making surplus intrastate gas available to the interstate market. Nevertheless, no long-range encroachment on gas supplies for the relatively high priority residential and commercial markets can be foreseen.

2.6.3 Public Utility Regulation

One of the major institutional problems is the question of utility regulation. The HAHP-ICES provides a utility service to occupants of buildings served by an ICES and may create problems of regulation depending upon how the system is designed and operated.

In this section, the HAHP is considered generically and consequently the institutional problems relating to the generation and use of electricity are discussed even though the HAHP considered in this study does not generate more electricity than can be used internally within the unit. The HAHP designed in this study avoids the complications imposed by the sale of electricity but it is necessary to discuss them in order to cover the more general case where the sale of electricity may be necessary or desirable to maximize the economic advantages of the HAHP-ICES.

2.6.3.1 Electric Utility Considerations

There are virtually no areas where an ICES might be built that do not already have a franchised electrical utility service provided exclusively by one company. Thus, if the ICES proposes to supply electricity, it must be shown that this does not infringe upon the exclusive franchise held by the existing electric utility. The criteria for this vary since decisions on this question result from court cases involving complex situations not easily extrapolated to other cases.

Generally, the criteria have hinged on the question of whether electricity has been resold; that is, produced for others than those involved in the project, who pay for the electricity and may, therefore, have need for the protection of a regulatory agency. In many areas, the reselling of electricity to tenants of a building by the owner, who buys electricity from the local utility, is prohibited. Where the electricity is generated on site more lenient interpretations have been made, or electricity has been provided as part of other services such as rental costs.

Experience with total energy systems has shown that they are more attractive economically where electricity generated on site can be resold to occupants or tenants of the buildings being served. Where this is permitted, the question of utility regulation may hinge on other factors.

In a number of instances, the question was whether utility service lines required the crossing of public property, such as a road, or required an easement across other private properties. It seems clear that an ICES system distributing electricity wholly within a single property is less likely to be interpreted as a public utility (thus, violating the franchise of the existing utility) than one which extends over several properties that are not contiguous.

The base case, as well as the site-specific case, provides only enough electricity for internal use. It has been presumed that legal and institutional problems in interfacing with the electric utility grid would make any such arrangement economically unattractive. However, it may be instructive to evaluate the alternative of involving the local electric utility so that the distribution of electricity is done by the utility itself. This may be difficult to do. In the past electric utilities have shown little interest in sponsoring total energy systems, although in many cases, such sponsorship may have had benefits for the electric utility. Selling the electrical output of the HAHP to the electric utility grid has been resisted by most utilities because of the operational problems introduced. This resistance may be eliminated by regulations, but the operating costs added must eventually be absorbed by someone. Initially, when these costs are small, other rate payers may be required to absorb them, but as they increase with larger numbers of such systems, the added cost must be charged to those who incur them. This may not make such utility connections prohibitive, but care must be taken to include such costs in HAHP-ICES planning, where this alternative is used.

2.6.3.2 Gas Utility Considerations

Regulated gas utility does not pose the same problems as the electric utility. A gas utility has a franchise to distribute and sell utility gas exclusively in a given area. The HAHP may or may not be a customer of such a utility, but it cannot be construed as a competitor. Thus, the gas utility may be a very effective supporter of a HAHP since it represents a significant new customer that may (or may not) choose to use gas as a fuel.

2.6.3.3 Other Utility Considerations

In some urban areas utilities have been franchised to distribute steam for heating purposes. These have usually been granted to, or purchased by, gas or electric utilities who are in a favorable position to provide such services.

In recent years, it has not been an attractive business because of the high cost of installing steam (or other types) heat transporting lines. It has usually proved cheaper to install and operate gas-, or oil-fired combustion equipment than to run heating lines to buildings that may even be adjacent to existing buildings served by central steam systems. There are exceptions to

this, such as military bases, college campuses, industrial plants, and similar communities where heating system piping may be carried overhead or buried in easily accessible trenches. Thus, although there are precedents for public utility regulation of heating (and cooling) systems, they are uncommon and many states have no experience with them.

Experience with total energy plants suggest that as long as such heating and cooling system lines do not traverse public property and/or require easements to other property, they may not come under public utility regulation. However, this understanding does not preclude a public utility regulatory body from regulating, or obtaining authority to regulate, the rates charged for heating, cooling, or electrical service when such services are sold to building tenants or owners. Generally, if such tenants or owners are few in number, they are assumed to have sufficient bargaining power with their supplies that public regulation is unnecessary. However, when the number becomes large enough so that individual dissatisfaction cannot be redressed by the principals, public regulation may be imposed even where there is no precedent.

In this context, the HAHP must be capable of providing heating, cooling, and electrical service at rates and with reliabilities comparable to other alternatives. If that can be done, there should be little justification for direct public regulation. If such utility services prove to be more expensive or less reliable (even though they are more energy efficient), they may lead to public regulation. Such regulation could, in turn, lead to discouragement of the HAHP-ICES concept if it results in unattractive rates of return to the investors. Because of the greater financial risk, the return on investment (ROI) for a HAHP-ICES must be greater than the conventional ROI for a gas or electric utility.

This is an institutional hazard that can best be avoided by ensuring that a HAHP is applied only in situations where it can provide reliable service at competitive costs.

2.6.4 ICES Ownership

There are many considerations involving ownership of the ICES that may affect the success of the concept.

2.6.4.1 Ownership by Private Real Estate Developer

Traditionally, the real estate developer has been a person who acquires a piece of land and builds some useful structure on it to be sold to some interested buyers. Sometimes he finds it advantageous under present tax laws to lease or rent the property to others rather than selling it outright. For example, the developers of shopping centers have generally found that it is more attractive to build and operate a shopping center than to build and sell it in our present business economy.

In either case, he is interested in maximum return on investment. A HAHP-ICES is useful to the developer only to the extent that it either improves the chances of success of his venture, or increases the return on investment. If he chooses to sell his property, he must persuade the buyer that the presence of a HAHP-ICES has made the property more valuable. Thus, whether he builds for sale, or for his own operation, the HAHP-ICES must improve the prospective rate of return for it has no other attraction — at least not in today's real

estate markets. To do this, it must offer a higher rate of return on its capital investment than does the building, or building complex, itself.

Experience with total energy systems has shown that many real estate developers lack the confidence to build and operate a total energy plant that will produce a greater rate of return than they can achieve in the real estate development business in which they consider themselves to be more competent. That is, they prefer to invest in the business they understand. In this situation the HAHP-ICES total energy system competes not against utility service costs but against real estate development/operating returns — and with some prejudice toward real estate development.

In view of these factors, the direct ownership of a HAHP-ICES by the building developer may not provide the most favorable conditions for the acceptance of such systems.

2.6.4.2 Institutional Ownership

When a building complex is owned by some institution, such as a municipality, university, public hospital, or other similar organization, the methods of making economic comparisons may be more favorable to the HAHP-ICES. In these cases, the buildings may be financed by a public bond issue. The retirement of bonds and the operating expenses must be covered by tax levies, but the concept of a rate of return is not involved, since the building complex generates no income, per se. Public and other institutional administrators generally prefer to accept higher first costs in order to obtain lower operating costs. Since the retirement of a bond is not considered part of the operating cost, the comparison is made between the utility service costs of a HAHP-ICES and those of the conventional utility services. The cost of retiring a bond, particularly if it is tax exempt, is less than the expected rate of return on a real estate investment. Thus, the analysis in such cases is apt to be more favorable to the HAHP with its relatively high first cost and lower operating cost than in the preceding case.

2.6.4.3 Energy Company Ownership

As in the case of total energy systems in the past, the building developer may elect to subcontract the utility services to an "energy company" which in effect competes with conventional utilities to provide utility services, but includes many services not offered by conventional utilities.

This alternative has a distinct advantage to the building owner in that it relieves him of any responsibility for operation and maintenance of the energy system — to a greater extent than even the use of a conventional utility service. He no longer need concern himself about furnace repairs, utility service interruptions, etc. However, he will still be held accountable by his tenants for the performance of his "energy subcontractor."

This alternative may require that all of the costs associated with the subcontracted energy service be identified with the energy company. Maintenance costs of the energy service facilities cannot be included in building maintenance costs as would be done ordinarily, for example. Thus, the full cost of energy service to the tenant may reflect more costs than are conventionally

identified as utility expenses. In that case, the tenant should expect his energy bills to be greater than he would pay for conventional utility service. However, he may not understand this and, unless the energy company can provide service at costs comparable to conventional utility costs while absorbing the added expenses, the tenant may feel he is being overcharged. This could lead to direct regulation as discussed earlier.

In the case of an HAHP system, some components of the energy system have been left as part of the building expense rather than being included in the responsibility and costs of the energy company. Thus, unitary air-conditioning equipment in the residential buildings would not be included in the energy company's responsibilities. This was done to confine the facilities of the energy company to an easily definable area and minimize its involvement in the building designs. It also serves to prevent the transfer of certain conventional building expenses, such as unitary heating and cooling, to the energy company costs.

Another alternative is for the building complex manager to pay the energy company for the energy service collecting a fee from the tenants for the use of the energy. This may permit greater flexibility in apportioning energy related costs between rental expense and utility costs.

2.6.4.4 Condominium Ownership

There are certain additional institutional problems introduced when the buildings in an ICES are sold as condominiums. If a portion of the building complex is composed of condominiums, the ICES is much more likely to be subject to utility regulation and to violate the exclusive franchise of the local electrical utility, since it is providing utility services or electrical service to a number of independent property owners.

If the entire community consists of condominium owners and each owner owns a share of the ICES, it becomes a cooperative venture providing energy for its owners to the general public. If a separate company owns the ICES but contracts with the condominium owners exclusively, the situation is less clear. But if the energy company also owns and operates other such ICES or contracts with various energy users, the justification for public regulation increases.

In this context, HAHP serving the type of load selected for it in this study is more likely to become involved in the complex aspects of the utility regulation question. Although some precedents have been established in the development of conventional total energy systems, there is no clear body of law pertinent to these systems that can assure that the basis on which an ICES is planned will remain valid during the economic life of the project.

In addition to the questions of regulation, condominium ownership introduces questions of legal liability of the owners, insurance coverage, and system replacement costs, if incurred.

The general lack of experience with these problems causes resistance to the acceptance of the concept not only by the owners and prospective tenants, but by the system developers as well. It is important, therefore, to select applications for the HAHP where it can be installed and used efficiently and

economically with a minimum of untried contractual arrangements. It is not that such arrangements may not be advantageous, but that they may introduce unforeseen side effects that are undesirable, or even intolerable.

2.6.4.5 Utility Ownership

There are a number of attractions to utility ownership of a HAHP-ICES, particularly a joint utility where one exists. All utilities strive to achieve maximum load factors throughout the year. Electric utilities welcomed air-conditioning loads until their systems peaked in the summer and have since favored electric heating in the winter to balance the system. Gas utilities have never been able to develop heavy summer loads except in industrial categories. Ideally, a joint utility would like to provide gas-powered air conditioning in the summer and enough electric heating in the winter to reduce the annual fluctuations in both gas and electric loads.

The HAHP provides a gas utility with an excellent opportunity to increase its summer gas load and also reduce its winter peak loads. If it is also a joint utility, it has no problem of infringing on the electric utility franchise. In addition, utilities generally are allowed rates of return on their investments that are lower than a real estate developer or an unregulated energy company would expect to achieve. Thus, a utility may be willing to invest in an ICES that promises a rate of return that would be considered marginal or inadequate by a private businessman.

While these incentives exist, there are also problems associated with utility participation. Some public utility franchises restrict a utility from participating in such ventures making it necessary to participate through a subsidiary company. This may be desirable for other reasons as well. In any case, the added administrative expense of a subsidiary requires that there be at least an expectation of some sizable participation in such ventures to absorb that expense.

Gas utilities have some history of participation in total energy plants and because of the potential customer value, they have a stronger incentive than those of an electric utility. In the past, the electric utilities have not shown much interest in total energy plants or cogeneration schemes. The cost of putting electricity into the electrical supply grid from a small ICES plant is generally higher than the cost of putting centrally generated electricity into the same grid. Therefore, the compensating revenue from heating and/or cooling must accrue to the utility in amounts sufficient to offset the added cost of localized generation and the loss of revenue from utility-supplied electric heating and cooling loads. Electric utilities are becoming capital resource limited. Increasing inflation has reduced the capacity of depreciation flow to finance new generating plants and environmental restrictions have added new capital requirements. This capital problem may become more acute in the next several years if new capacity additions are required.

Since the industry is dedicated to meeting the load, the first priority for available capital will be to provide capacity to meet the electric-load demand. Diverting capital to the generation of revenue from heating or cooling services will be attractive only if by so doing it improves its position with

regard to meeting the load. That is, if investment in an ICES diverted electrical demand to direct heat or cooling so that, on a dollar-for-dollar investment basis, the utility could serve a larger energy load per dollar through an ICES than through conventional electric generation, it could be attractive.

An examination of this question is beyond the scope of this study. Although this concept has not been demonstrated in the past, it is not inconceivable that future economic developments might make it feasible in the future. In any case, public policies directed toward broadening the ability and freedom of a utility to participate in the operation of ICES equipped with HAHP may further increase the incentives already present for utility participation.

2.6.5 Resale Considerations

2.6.5.1 Institutional Ownership

Where an HAHP-ICES is built by an institutional owner, there is less consideration given to resale problems than in the case of private investor ownership. In some public housing, consideration of eventual resale of individual dwellings to tenants as condominiums may be a factor in the project planning, but more often the project is assumed to remain in the hands of the original owners throughout the economic life of the buildings.

Under these circumstances, an unforeseen resale would expose the project to market evaluation by real estate appraisers and the presence of the HAHP-ICES could be a plus or minus factor in that appraisal. However, it is not likely that such a resale appraisal value would be a strong factor influencing the initial planning decisions for the project at the time of construction.

2.6.5.2 Private Investor Ownership

An HAHP-ICES built by a private investor may offer more serious problems because of the stronger possibility of resale during the economic life of the project.

If the entire project is to be considered for resale to another investor, the presence of the HAHP-ICES may seriously affect the resale value. If the HAHP-ICES is included as part of the sale, its performance must not seriously detract from the value of the property and should preferably enhance its value. As discussed earlier, we may assume that the HAHP-ICES did originally promise to improve the value of the property or it would not have been chosen for the design. Thus, it is only the question of whether the HAHP-ICES lives up to the promises made for it originally.

The possibility of the HAHP-ICES not working out favorably thus becomes a depressing influence on the original selection of the HAHP-ICES at the time the project is planned. If the system performs as predicted, it may be an asset at the time of resale. This should be true if the HAHP-ICES is owned by a separate energy utility as well as by the building owner. It would also apply to sale of the residential buildings as condominiums. If the HAHP-ICES has been an asset for the owners and tenants, resale should be enhanced by its presence; if it has not been of benefit it will depress the resale value. For this reason, many investors may be reluctant to become involved in the HAHP-ICES concept until an acceptable performance record has been demonstrated.

2.6.6 Zoning Regulations, Building Codes and Standard Practices

Every community is subject to a great number of federal, state, and local regulations governing the construction and use of the many different types of buildings and activities carried on within an ICES. A number of the more common categories are discussed below, noting the problems and benefits that each may have on an HAHP-ICES.

2.6.6.1 Zoning Regulations

The controlled use of land is an important factor in all communities. Certain land owners depend upon stable zoning laws for the protection of their real estate investments and the businesses that may be conducted in them. Other land owners seek to change the zoning laws to permit them to develop property and to engage in other business activities.

The unavoidable conflicts that occur are usually resolved at the local level. This process tends to favor the interests of existing property owners. In established neighborhoods there is a tendency to resist change. In undeveloped areas the potential developers may have more influence. However, conflicts still occur because of the potential competition among developers. For example, two residential building developers may disagree on local zoning requirements for lot sizes, street layouts, or building designs that might favor the competing developer. On the other hand, both residential builders might support a zoning change that would permit a convenient shopping center or school.

The approval of a zoning change to permit an ICES may be more controversial than many zoning problems because the ICES may incorporate features that are acceptable to some but objectionable to others. The more complex it is, the more people can find some undesirable feature.

In the present case, some may accept two-story multi-family dwellings but object to a six-story building of any kind. Others may see a zoning change that would allow an energy conversion plant within the ICES as setting a dangerous precedent. Others may agree to the plant only if elaborate steps are taken to shield the plant from view and to insulate the area from noise — perhaps by requiring unacceptable spacing from other buildings.

The redevelopment of depressed urban areas presents a relatively favorable opportunity for HAHP-ICES development and rezoning for this purpose should be relatively easy due to the following factors:

- Because of the depressed state of real estate values, there is apt to be less resistance to change.
- Opportunities for government support, both financial and political, are usually better.
- The energy intensiveness of the redeveloped area is usually greater than in the preceding urban area and energy utilities can be expected to support the redevelopment.

There are no simple or even predictable answers to the many problems that will occur in siting an ICES. It is necessary that the projected economics be sufficiently favorable that the time and expense of obtaining favorable zoning decisions and of complying with provisions imposed by opponents can be absorbed without crippling the project.

For the site-specific community in Monroeville, the local zoning ordinance was examined to determine the suitability of the HAHP-ICES to the plans of that municipality.¹³ The exact location is presumed to be that being developed by U.S. Steel Realty Development Division. The area had been zoned as a special use district and is currently being rezoned, most likely to a multiple-family residential district, or developed as a Planned Unit Development (PUD).

The HAHP-ICES thermal utility is envisioned to be a viable business entity functioning as a utility. As such, it would be consistent with several Monroeville development objectives as follows:

- Increase the economic base
- Provide the necessary infrastructure for a utility
- Would not contribute to visual blight
- Encourage utilities to improve and extend services.

Specific zoning difficulties for the HAHP-ICES described in this study are not expected.

2.6.6.2 Government Financial Support

If government financial support is required by the project, the conditions for approval of that support should be carefully examined, particularly if more than one government agency is involved. The conditions imposed by one agency may conflict with local zoning or building codes or may even conflict with the requirements for support by other government agencies. At one time, the State of New York specified that windows in schools be of certain dimensions that conflicted with Federal Government specifications in such a way that either state or federal supporting funds could be obtained, but not both.

This problem can be avoided, of course, if the ICES is privately financed. However, institutional ownership was suggested earlier as being a more favorable prospect for ICES ownership than a private investor. Government support is more likely among institutions, but the conditions of such participation may be known quite early in the development of the project. Thus, there usually is time to explore any conflicts and assess any potential added costs that may be imposed by government support.

It is interesting to note that if the boiler of the HAHP-ICES was subject to federal inspection and control, the municipal code of Chicago and the regulations of Pennsylvania would not apply.^{14,15}

2.6.6.3 Building Codes

Although a valiant attempt has been made to establish national building codes, there is still a confusing array of state and local building codes that govern building construction in all areas. Most of them were established many years ago and were designed around materials and practices that were specified in the code at the time of its issue. Often, such codes are defended by labor unions having a vested interest in the protection provided by the code, even though better materials and labor-saving practices are available. This problem is most acute where new or unconventional systems are installed. Jurisdictional disputes may be created regarding not only the applicable code, but the category of labor permitted to do the installation.

An ICES may present a greater number of such situations because of the use of unconventional energy systems such as the HAHP, solar systems, etc., as well as unusual energy transportation and storage systems.

Where code compliance and union labor issues can be anticipated, prior approval should be requested for the questionable practice. In doing this, precedents elsewhere and alternative procedures should be known and documented as well as possible. This will minimize costly delays due to recertification and/or labor interruptions at the time the work is done.

No simple resolution of these problems can be anticipated. It is a perennial problem area in which success is a matter of degree for everyone involved. Nevertheless, careful planning and anticipation of problems can pay dividends in preventing unexpected cost increases that reduce economic benefits and discourage follow-on projects.

Precedents established (or discontinued) in initial HAHP-ICES projects will set the patterns for many years to come. Many later projects will benefit (or suffer) from the decisions arbitrated during the early projects. Thus, there are sound justifications for broader industry support than can be funded by the initial project managers alone. Garnering such support may be more successful if the long-range outlook for the system appears promising. This again suggests that initial projects should be carefully selected to promote significant advantages over conventional alternatives.

2.6.6.4 Standard Practices

No state has a standard practice document pertaining to the design, installation and operation of gas-fired heat pumps. Thus, each state or local code enforcement agency must be guided by other standards and practices that are deemed to be pertinent although prepared without consideration of gas-fired heat pumps specifically.

Use of such existing standards may require the adoption of practices, design specifications, and performance requirements inappropriate to the heat pump applications. Such practices could inhibit the use of heat pumps and diminish the energy savings they promise to achieve.

To explore the problems of conforming to local codes, representatives of the following agencies and communities were contacted:

- Building Officials and Code Administration International, Inc. (BOCA)
- City of Chicago, Illinois
- Municipality of Monroeville, Pennsylvania.

Monroeville, the location for the site-specific case, has adopted the BOCA codes. It also follows the National Electrical Code, Pennsylvania boiler regulations, and the Allegheny County plumbing code.¹⁶

To meet the existing BOCA codes, the following requirements must be met:

- ASME boiler construction standard
- One hour fire-resistant rated wall with Class C fire door
- Provisions for combustion air and venting
- Installation permit
- Annual inspection
- Certified boiler operator.

To meet the Pennsylvania boiler regulations, the following may be required:

- Approval of the special HAHP-ICES boiler design by the Department of Environmental Resources prior to construction
- Inspection by the department during construction
- Provisions for a low water fuel cutoff with a manual reset
- Blowoff tank
- Outside discharge of safety valves
- Two means of egress from the boiler room.

The HAHP-ICES is expected to meet the applicable code requirements. However, only two certified boiler operators have been specified in this analysis. This assumes the adoption of a suitable change in the BOCA requirement for surveillance during high-pressure boiler operation.

There may be considerable merit to creating a generic heat-actuated heat pump standard to be applied specifically to heat pumps. This standard would be derived largely from existing heating, cooling, and ventilating industry standards, deleting or modifying inappropriate or unnecessary requirements, and adding such new requirements as may be necessary to ensure effective performance of a heat pump.

If such an industry standard were prepared and accepted in a number of key states, it would provide several benefits in gaining acceptance of heat pumps. These are:

- A single authoritative group would produce a consistent standard once and for all.
- The problems of seeking piecemeal deviation from existing practices on a local case-by-case basis could be avoided.
- The resulting standard would be broadly applicable and could be adopted by each state or local authority without serious modification.
- Acceptance would be more readily attainable by establishing the standard prior to widespread use of heat pumps, thus avoiding the accommodation of existing local practices.

Some of the existing codes that would be embedded in such a heat pump standard are listed below.

1. ASME Safety Code for Controls and Safety Devices for Automatically-Fired Boilers. ASME Safety Code #CSD-1.
2. ASME Construction Code for Power Boilers. ASME Pressure Vessel Code Section 1.
3. Underwriters Laboratories Standard for Safety for Heat Pumps. UL #559.
4. American Society for Testing Materials Standards specified for all structural materials.

One difficulty already anticipated in the commercialization of gas-fired heat pumps is the present requirement governing the operation of high-pressure steam boilers. Many communities require that a licensed operating engineer be on duty at all times where a high-pressure steam boiler is in operation. Experience has shown this to be a prudent requirement where the potential hazard of an explosion is significant. However, small boilers and steam generators containing relatively small amounts of superheated water that can flash to steam in the event of a malfunction, present far less hazard and can be designed to minimize this risk sufficiently to make a full-time operating engineer unnecessary. By incorporating the necessary design requirements, and stipulating size and pressure limitations that would avoid the hazards of boiler explosion, an acceptable code might be established that would eliminate the need for an operating engineer in many situations. This would significantly reduce HAHP operating costs, particularly in smaller systems, and would facilitate the commercialization of the concept.

A thorough review of the existing standards will uncover many such instances where revisions can be made to update or eliminate existing requirements that are no longer effective or appropriate. Thus, the preparation of a generic HAHP code may offer an opportunity to establish an applicable equipment standard more rapidly and more effectively than the piecemeal revision of existing standards.

2.7 Summary

- The HAHP-ICES can offer economic advantages over a conventional energy supply system in most of the geographic areas of the country, provided that an appropriate combination of residential and office buildings are selected. The potential national market for residential/office real estate developments comparable to the HAHP-ICES base case is roughly 390 per year.
- However, the market acceptance of the HAHP depends upon the market acceptance of the ICES concept.
- There is no obvious basis for predicting the timing or extent of the market penetration of the ICES, since its future acceptance appears to hinge upon the creation of artificial stimulants which, at present, are not well-defined and may be uncertain. However, scenarios based on different pessimistic-optimistic market capture assumptions suggest that the market penetration potential for the 1980-1990 time frame could be as high as 411 systems, equivalent to 711 90-hp heat pumps.
- If this market penetration potential could be realized, the potential energy savings for the country would be 6.4×10^5 bbl oil equivalents per year for the most optimistic case considered.
- No long-term shortage of natural gas is foreseen that would inhibit the development of the HAHP.
- There are many institutional questions which cannot be quantitatively evaluated, but which may introduce additional costs at the time of construction.
- The HAHP-ICES should be able to meet applicable codes if sited in Monroeville, Pennsylvania, assuming that two certified boiler operators satisfy the BOCA requirement for high-pressure boiler surveillance.
- Compliance with building codes may entail construction delays if novel design approaches result in unforeseen conflicts with existing practices.
- A HAHP standard code could offer a means of resolving many compliance problems in advance, saving time and expense.

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3. EXPECTED PERFORMANCE

In the following sections, the methodology used and the results of the analysis performed to evaluate performance of the heat pump portion of the central plant compared to a more conventional system in both its base-case and site-specific applications are presented.

The base-case application of the HAHP-ICES concept was a non-site-specific application of HAHP-ICES in which the sensitivity of the performance, and ultimately the economics of the concept to climate, load mix, utility rate structures, and other economic parameters was explored. The base-case application of the HAHP-ICES concept consists of a load mix of a single, six-story, 59,000 ft² office building and five, two-story, 24-unit low-rise apartment buildings. Base-case thermal loads for heating and cooling are based on Chicago weather.

The site-specific application explored the performance and economics of the HAHP-ICES concept in a particular site — Monroeville, Pennsylvania; a particular load mix of residential, commercial, and retail buildings corresponding closely to a proposed planned community, and utility rates currently applicable at the site. The site-specific application of HAHP-ICES consists of a load mix of 42 townhouses, 120 low-rise dwelling units in five two-story buildings, 520 high-rise dwelling units in five six-story buildings, 124,000 ft² of office space in one building, and 135,000 ft² of retail space under one roof. Site-specific thermal loads for heating and cooling are based on Pittsburgh, Pennsylvania weather.

In this section, the characteristics of the HAHP-ICES central plant and the conventional system to which it is compared are presented. Among the characteristics discussed are full and peak load performance of both the heat pump and conventional systems. The reader is referred to the discussion under Section 1 for a review of the HAHP-ICES system description. A summary comparison of the major heating and cooling components in the baseline conventional system and the HAHP-ICES is shown in Table 3.1. A summary of the major heating and cooling components in the site-specific conventional system and the HAHP-ICES is shown in Table 3.2.

Following this discussion, the results of performance evaluations of conventional HVAC systems and HAHP-ICES as applied to the base-case, mixed-load community and site-specific community are presented. The results are presented in terms of primary-energy consumption by the system. Annual performance of HAHP-ICES was developed using a computer code that matches 8760 hours of thermal load data against heat pump performance using a control philosophy that maximizes efficient use of energy. Performance of conventional HVAC systems were modeled using the Meriwether Code. In addition, the sensitivity of the base-case system performance to climate and load mix is discussed. The first- and second-law performance of conventional HVAC components and HAHP-ICES in both heating and cooling modes is discussed. Major findings from the investigation of conventional systems and HAHP-ICES are summarized.

Table 3.1. COMPARISON OF MAJOR HEATING AND COOLING COMPONENTS IN BASELINE CONVENTIONAL SYSTEM AND HAHP-ICES

<u>Function</u>	<u>Baseline System Conventional Equipment</u>	<u>HAHP-ICES</u>
<u>Office Building</u>		
Heating	Heat reclaim chiller Electric boiler	HAHP operated in heat re- covery or outside air heat source mode; turbine con- denser heat; direct from boiler
Cooling	Electric motor-driven chiller	Turbine-driven chiller; electric motor-driven chiller
Domestic Hot Water	Heat exchanger plus storage tank interfaces with elec- tric boiler	Winter: same as heating Summer: turbine condenser heat; direct from boiler
Distribution System	6-pipe thermal system within building plus connection with electrical grid	6-pipe thermal system within building interfacing with HAHP-ICES central plant, plus connection with elec- trical grid
<u>Residential Building</u>		
Heating	Unitary gas-fired forced air furnace	Turbine condenser heat; HAHP operated in heat re- covery or outside air heat source mode; direct from boiler; distribution system interfaces with perimeter baseboard units in each apartment
Cooling	Unitary central air-to- air electric air condi- tioners in each apartment with roof mounted condenser	Unitary through-the-wall
Domestic	Individual storage-type gas-fired water heaters	Central circulating system
Distribution System	Gas and electricity pro- vided by utilities	2-pipe hot-water system to each apartment within build- ing; 2-pipe DHW system; elec- tricity to each apartment
Flue	Required for each apartment	Not required

Table 3.2, Part 1. COMPARISON OF MAJOR HEATING AND COOLING COMPONENTS
IN CONVENTIONAL SYSTEMS AND HAHP-ICES SITE-SPECIFIC CASES

<u>Function</u>	<u>Site-Specific System Conventional Equipment</u>	<u>Site-Specific HAHP-ICES</u>
<u>Office Building</u>		
Heating	Heat reclaim chiller Electric boiler	HAHP operated in heat re- covery or outside air heat source mode; turbine con- denser heat; direct from boiler
Cooling	Electric motor-driven chiller	Turbine-driven chiller; electric motor-driven chiller
Domestic Hot Water	Heat exchanger plus storage tank interfaces with electric boiler	Winter: same as heating Summer: turbine condenser heat; direct from boiler
Distribution System	6-pipe system within building plus connection with electrical grid	6-pipe system within build- ing, 6-pipe system from central plant plus connec- tion with electrical grid
<u>Retail Store</u>		
Heating	Gas boiler, variable air volume distribution system	Turbine condenser heat; HAHP operated in heat re- covery or outside air heat source mode; direct from boiler; variable air volume distribution system
Cooling	Electric chiller	Turbine-driven chiller; electric motor-driven chiller
Domestic Hot Water	Not provided	Not provided
Distribution	Gas and electricity provided by utilities	2-pipe system plus connec- tion with electrical grid
Flue	Required for boiler	Not required
<u>High Rise</u>		
Heating	Central boiler inter- facing with fan coil in each apartment	Turbine condenser heat; HAHP operated in heat recovery or outside air heat source mode; direct from boiler; distri- bution system interfaces with fan coil in each apartment

Table 3.2; Part 2. COMPARISON OF MAJOR HEATING AND COOLING COMPONENTS
IN CONVENTIONAL SYSTEMS AND HAHP-ICES SITE-SPECIFIC CASES

<u>Function</u>	<u>Site-Specific System Conventional Equipment</u>	<u>Site-Specific HAHP-ICES</u>
Cooling	Central electric chiller	Turbine-driven chiller; electric motor-driven chiller
Domestic Hot Water	Central domestic hot water system	Central circulating system; storage tank with heat exchanger, no burner
Distribution System	2-pipe heating/cooling system plus 2-pipe DHW system within building; Gas and electricity supplied by utilities	2-pipe heating/cooling system plus 2-pipe DHW system within building; 4-pipe system from central plant; connection with electrical grid
Flue	Required	Not required
<u>Low-Rise and Townhouse</u>		
Heating	Unitary gas-fired forced air furnace	Turbine condenser heat; HAHP operated in heat recovery or outside air heat source mode; direct from boiler; distribution system interfaces with perimeter baseboard units in each dwelling
Cooling	Unitary central air-to-air electric air conditioners in each apartment with roof mounted condenser	Unitary through-the-wall electric air conditioners. Low-rise: 2/apartment; Townhouse: 3/unit
Domestic Hot Water	Individual storage-type gas-fired water heaters	Low-rise: central circulating system. Townhouse: individual water heaters with heat exchangers; no burner
Distribution System	Gas and electricity provided to each apartment	2-pipe hot water system to each apartment; 2-pipe DHW system within low-rise units; connection with electrical grid
Flue	Required for each apartment	Not required

3.1 Performance Characteristics of the HAHP-ICES

In this section the full load performance of the steam generator and turbine and full load heating and cooling performance of the HAHP-ICES central plant are discussed. The generation of electricity by the system to help meet central plant distribution pumping and cooling tower loads is also discussed. The basic assumptions underlying the development of central plant heating and cooling performance are summarized in Section 9.6.3.

3.1.1 Input/Output Performance of Steam Generator and Turbine at Full Load

The thermal input/output characteristics of the steam generator and turbine combination have been determined. These consist of the input requirements to the 83% efficient boiler at full load and the turbine exhaust heat at the turbine condenser. The overall input/output characteristics of the steam generator and turbine are determined by its efficiency curve (see Section 9.6.6) the boiler efficiency, and the requirements of the water delivery temperature schedule for sufficient temperature differences for adequate heat transfer (see Section 9.6.4). The input-output characteristics are presented tabularly for 10°F temperature increments in Table 3.3.

Table 3.3. INPUT/OUTPUT PERFORMANCE OF THE STEAM GENERATOR AND TURBINE AT FULL LOAD

Ambient Temperature (Tamb), °F	Turbine Condenser Temperature, °F	Efficiency, %	Boiler Input, Btu/hr	Condenser Heat Available, Btu/hr*
0 and Below	200	0.22	1.2544×10^6	0.76×10^6
+10	190	0.237	1.1644×10^6	0.6891×10^6
+20	180	0.254	1.0865×10^6	0.6276×10^6
30	170	0.270	1.0221×10^6	0.5769×10^6
40	160	0.284	0.9717×10^6	0.5371×10^6
50 and Above	150	0.296	0.9323×10^6	0.5061×10^6

$$\text{Boiler Input} = (90)(2545.1)/(\text{Efficiency})(0.83)$$

$$\text{Condenser Heat Available} = \left[\frac{(90)(2545.1)}{\text{Efficiency}} \right] - \left[\frac{(90)(2545.1)}{(0.95)} \right] 0.95$$

* Assumes turbine jacket losses equal to 5% of output and condenser losses of 5%.

3.1.2 Heat Pump Performance in the Cooling Mode

The full-load performance of each turbine-driven heat pump module in the HAHP-ICES central plant in the cooling mode is summarized in Table 3.4. Full load turbine-driven mechanical cooling output ranges from 1.16×10^6 Btu/hr at an ambient temperature of 60°F (COP = 5.8), to 0.76×10^6 Btu/hr at 100°F (COP = 3.8). The overall cooling COP of the turbine-driven chiller, based on input to the boiler, ranges from 1.25 at 60°F to 0.82 at 100°F. Overall cooling COP does not include pumping and cooling tower fan requirements. Turbine-driven compressor horsepower requirements as a function of cooling load are summarized in Section 9.6.7.

Table 3.4. HEAT PUMP FULL LOAD COOLING PERFORMANCE

Ambient Temperature, °F	Full-Load Mechanical Cooling COP	Full-Load Mechanical Cooling Output, 10^6 Btu/hr	Overall Turbine-Driven COP
60	5.800	1.163	1.25
70	4.874	0.977	1.05
80	4.453	0.893	0.96
90	4.083	0.819	0.88
100	3.792	0.760	0.82

1. Full-load heat input to boiler = 0.9323×10^6 Btu/hr.
2. Full-load work output from turbine = 78.76 hp.
3. Full-load turbine condenser heat = 0.5061×10^6 Btu/hr. Condenser heat used to meet domestic hot-water requirements as necessary. Excess condenser heat rejected to cooling tower.
4. Turbine-driven COP based on boiler input. Turbine-driven chiller COP does not include distribution pumping or cooling tower fan loads.

In the base case, the cooling tower is sized at a heat duty of 3×10^6 Btu/hr to handle 100% of the steam turbine condenser heat load, the steam turbine-driven chiller, and backup electric chiller refrigerant condenser heat load.

In the site-specific case, each steam generator and turbine is equipped with a cooling tower. The cooling tower is sized at a heat duty of 0.5×10^6 Btu/hr to handle 100% of the steam turbine condenser heat. Each steam turbine-driven heat pump is equipped with a cooling tower sized at 1.0×10^6 Btu/hr to handle the refrigerant condenser heat load.

Supplemental cooling is required in both the base and site-specific cases. Supplemental cooling is provided by electric-driven chillers. Supplemental cooling capacities for the base case are summarized in Section 9.6.10; for the site-specific case in Section 9.6.11.

3.1.3 Heat Pump Performance in the Heating Mode - Internal Heat Recovery Operation

In applications where a year-round cooling load exists, especially during the heating season, a source of heat for the HAHP-ICES central plant is the recovery of heat from the building space that must be cooled. The full-load, pumped-heat heating performance of each turbine-driven heat pump module ranges from 0.80×10^6 Btu/hr at -10°F to 0.66×10^6 Btu/hr at 30°F , and up to 0.80×10^6 Btu/hr at 50°F ambient. The drop in pumped heat is due to the characteristics of the water temperature delivery schedule. Corresponding cooling output ranges from 0.60×10^6 Btu/hr to 0.46×10^6 Btu/hr at -10°F and 30°F ambient, respectively. Cooling output at 50°F is 0.60×10^6 Btu/hr. The heat-pump heat output is supplemented by turbine exhaust heat. The addition of turbine exhaust heat results in full-load total heat outputs ranging from 1.56×10^6 Btu/hr at -10°F to 1.31×10^6 Btu/hr at 50°F . Corresponding overall heating COP's, based on input to the boiler, range from 1.25 to 1.41 at -10°F and 50°F , respectively. The overall heating COP does not include pumping power requirements. The performance of the heat pump in internal heat recovery operation is summarized in Table 3.5. Part-load performance of the heat pump is summarized in Section 9.6.8.

Supplemental heating is required in both the base and site-specific cases. Supplemental heating is supplied by low-pressure boilers with full-load efficiencies of 83%. Sizing of the supplemental boiler in the base case is discussed in Section 9.6.12. The capacities of the supplemental boilers used in the site-specific case are presented in Section 9.6.13.

The question arises as to whether there exists sufficient simultaneous cooling and heating loads in the community served by HAHP-ICES to make operation of the HAHP-ICES central plant in an internal heat recovery mode worthwhile. Looking at typical thermal loads in the base case office building, it is found that when the ambient temperature is above 30°F , after satisfying the office heating load (typically about 0.2×10^6 Btu/hr), the pumpable heat available at the heat pump refrigerant condenser in internal heat recovery operation is about 0.5×10^6 Btu/hr. Average residential heat loads in the base-case community are about 1×10^6 Btu/hr, thus heat pump refrigerant condenser heat can make a substantial contribution to satisfying residential heat loads. In the base-case community, these conditions of simultaneous heating and cooling load frequently exist. This suggests that allowing the heat pump unit to recover heat from internal cooling load is an efficient way to operate the HAHP-ICES. Statistics on the performance of HAHP-ICES in the site-specific case, where more than one heat pump unit is used to service community loads, further support the potential of heat pumping from internal cooling loads to serve heat loads elsewhere in the community. Specifically, when two heat pump units are used, there are 1537 hours out of 8760 hours that the heat pump units are operating in the internal heat recovery mode, at least at part load. With three heat pump units, there are 2573 hours of internal heat recovery operation; with four heat pump units, 3273 hours. Thus, there not only exists sufficient simultaneous heating and cooling loads to make internal heat recovery operation worthwhile within the community served by HAHP-ICES in the site-specific case, but the loads are large enough to operate up to four heat pump units, at least at part load, for a substantial amount of time.

Table 3.5. HEAT PUMP HEATING PERFORMANCE — INTERNAL HEAT RECOVERY OPERATION

	<u>Ambient Temperature, °F</u>				
	<u>-10</u>	<u>+10</u>	<u>+30</u>	<u>+40</u>	<u>+50</u>
Full-Load Input to Steam Generator, 10 ⁶ Btu/hr	1.25	1.16	1.02	0.97	0.93
Available Turbine Condenser Heat, 10 ⁶ Btu/hr	0.76	0.69	0.58	0.54	0.51
Full-Load Heat Pump Heating COP	4.00	4.00	3.30	3.65	4.00
Full-Load Cooling Output, 10 ⁶ Btu/hr*	0.60	0.60	0.46	0.53	0.60
Pumped Heat Available, 10 ⁶ Btu/hr	0.80	0.80	0.66	0.73	0.80
Full-Load Total Heat Output, 10 ⁶ Btu/hr	1.56	1.49	1.24	1.27	1.31
Overall Heating COP**	1.25	1.28	1.21	1.30	1.41

* Cooling is a co-product of internal heat recovery

** Overall heating COP is based on input to boiler. Heating COP does not include distribution pumping loads.

3.1.4 Heat Pump Heating Performance — Outside Air Source Operation

In the case of a load in which no internal source of heat is available, an alternative mode of operation for the heat-pump system is to utilize outside air as a heat source. In this mode of operation, the HAHP-ICES central plant uses a two-stage heat pumping design in which the first, or outside, compressor pumps heat from the outside to its condenser, which then functions as a heat source for the second, or inside, compressor. The inside compressor then pumps water from the thermal distribution system to the required send-out temperatures. Outside compressor maximum horsepower is 16 hp.

In the site-specific case, where more than one turbine is used, one turbine is used to generate electricity, and this turbine does not have outside air source heat pumping capabilities. The remaining turbines can use outside air (or internal heat recovery) as a heat source, but they follow the load and do not produce excess horsepower beyond the compressor requirement. Details of multiple compressor operation, in the site-specific case, are discussed in Section 3.3.2 on the simulation of the site-specific HAHP-ICES.

Heat-pump performance in outside-air-source operation is inferior to performance in internal heat recovery operation because of the lower source temperature. Pumped heat output ranges from 0.27×10^6 Btu/hr at -10°F to 0.60×10^6 Btu/hr at 50°F . With the addition of turbine exhaust heat to heat pump output, total heat output for the HAHP-ICES central plant ranges from 0.87×10^6 Btu/hr at -10°F to 1.11×10^6 Btu/hr at 50°F , with corresponding overall COP's based on input to the boiler ranging from 0.90 to 1.19 at -10°F and 50°F , respectively. The overall heating COP does not include pumping power requirements. Heating performance in outside-air-source operation, based on the maximum permitted total compressor input horsepower (outside compressor limited to an input of 16 hp), is summarized in Table 3.6. Part-load heating performance of the HAHP-ICES central plant is summarized in Section 9.6.9.

Table 3.6. HEAT PUMP HEATING PERFORMANCE — OUTSIDE AIR SOURCE OPERATION*

	Ambient Temperature, $^\circ\text{F}$						
	-10	0	+10	+20	+30	+40	+50
Full-Load Total Heat Input to Boiler, 10^6 Btu/hr	0.97	0.98	0.93	0.86	1.02	0.97	0.93
Total Compressor Horsepower Input	57.62	58.17	59.58	62.18	78.76	78.76	78.76
Turbine Condenser Heat Available, 10^6 Btu/hr	0.60	0.61	0.56	0.50	0.58	0.54	0.51
Pumped Heat Available, 10^6 Btu/hr	0.27	0.29	0.32	0.37	0.47	0.53	0.60
Heat Pump Heating COP	1.84	1.99	2.14	2.33	2.34	2.64	3.01
Full-Load Total Heat Output, 10^6 Btu/hr	0.87	0.90	0.88	0.87	1.05	1.07	1.11
Overall Heating COP	0.90	0.92	0.95	1.01	1.02	1.10	1.19

* Overall heating COP is based on input to the steam generator. Heating COP does not include distribution pumping loads.

Supplemental heating is required in both the base and site-specific cases. Supplemental heating is provided by low-pressure boilers with full-load efficiencies of 83%. Sizing of the supplemental boiler in the base case is discussed in Section 9.6.12. Capacities of the supplemental boilers used in the site-specific case are presented in Section 9.6.13.

Losses associated with defrost cycling of the outside air source evaporator have not been included within the central plant's performance. Energy for the defrosting of the evaporator coils is produced by diverting a portion of the steam generator flue gas through the coils. Because the defrost cycling would be based on demand, and because natural gas combustion products are notably cleaner than most other fuels, it is suggested that any corrosion problems would be insignificant. In addition, the effect of this flue piping, both in economic terms and thermodynamic changes in heat pump performance, is considered well within the design uncertainties in this study.

3.1.5 Generation of Electricity by HAHP-ICES -- Base Case

It is desirable to operate the HAHP-ICES central plant in a load-following configuration. This implies that the system tracks the thermal loads as closely as possible while simultaneously minimizing the rejection of thermal energy. In the base case, three factors come into play in the load-following behavior of the HAHP-ICES central plant; 1) modulation of the heat pump compressor, 2) modulation of turbine power output, and 3) generation of electricity by the turbine-driven generator to help satisfy distribution pumping and cooling tower loads. In the base case, the central plant is controlled by simultaneously balancing these three factors. (The base-case control philosophy is discussed in more detail in Section 3.3.2.)

The result of the load-following characteristics of the central plant is that the central plant pumping and fan loads are met or supplemented by the central plant whenever possible. These loads are met within this limitation: In the base case, unless sufficient turbine horsepower is available to produce at least 5 kW of electric power, no electricity is generated. The system never produces any excess electricity over that required by the central plant. In the base case, a special situation arises from limiting the outside compressor horsepower to 16 hp. At ambient temperatures below 30°F, the combined compressors cannot utilize the maximum available horsepower from the turbine, i.e., 78.76 hp. For example, at an ambient temperature of 0°F, total horsepower input to both compressors is 58.17 hp; remaining turbine horsepower may be used to generate electricity within the limitations that the system cannot produce electric power in excess of central plant requirements, and that the system is operated to minimize heat rejected to the cooling tower, such that total refrigerant and turbine condenser heat cannot exceed thermal loads imposed on the system by the community.

It must be mentioned that the assumption of an electrical grid connection in parallel with electrical generation on-site may result in an institutional barrier to implementation of HAHP-ICES because it is doubtful that an electrical utility would be favorably disposed to this interconnection. Such an arrangement might even result in higher electrical power rates than a system without this arrangement. However, the generation of electricity by HAHP-ICES is limited to supplying loads only in the central plant, such as cooling tower fans and distribution pumps; no electrical loads outside of the central plant are provided with on-site produced power. Thus, the dependence on ICES-produced power is minimal compared to the requirements for purchased electricity to operate, for example, the backup vapor compressor chiller; and problems of operation of the HAHP-ICES central plant to produce a limited amount of on-site electricity in parallel to the electric utility should be minimal. These considerations are, of course, equally applicable to the site-specific application of HAHP-ICES.

3.1.6 Generation of Electricity by HAHP-ICES — Site-Specific Case

It is desirable to operate the HAHP-ICES in a load-following configuration. This implies that the system tracks the thermal loads as closely as possible while simultaneously minimizing the rejection of thermal energy. In the site-specific case, four factors come into play in the load-following behavior of the HAHP-ICES central plant: 1) modulation of the heat pump compressor(s), 2) modulation of steam turbine power output(s), 3) generation of electricity by the steam turbine-driven generator to help satisfy distribution pumping and cooling tower loads, and 4) bringing individual steam turbines in or out of service. In the site-specific case, the central plant is controlled by simultaneously balancing these four factors. (The site-specific control philosophy is discussed in more detail in Section 3.3.2.)

The results of the load-following characteristics of the central plant is that the central plant electrical loads, such as distribution pumps and cooling tower fans, are supplied by the central plant whenever possible. In the site-specific case, these loads are met within the limitation that no electricity is generated unless generator load is at least 30% of full load steam turbine output. As in the base case, the system never produces any excess electricity over that required by the central plant. Note that in the site-specific case, only one steam turbine is equipped to generate electricity. This dedicated turbine may heat pump from an internal heat source only. Other turbines may heat pump from inside or outside as required. The only exception to this operating philosophy is that in the site-specific case, if only one turbine is used, it may be operated in one of three modes: 1) if an internal cooling load is available, it will heat pump from that heat source, modulating the turbine and compressor to follow the cooling load; 2) where there is no internal cooling load or the cooling load is less than 30% of the module's capacity, it will outside-air-source heat pump, modulating the turbine and compressor to follow the heat load; 3) when the heat load is low, the turbine will drive the generator to produce electricity as long as the generator load is such that the turbine is loaded to at least 30% of its full load output.

3.2 Performance Characteristics of Conventional Systems — Base and Site-Specific Cases

The base-case community consists of an office building and low-rise residential apartment buildings.

The site-specific case community also consists of an office building and low-rise apartment buildings; in addition, there are townhouses, high-rise apartment buildings, and retail store space. Thermal characteristics of buildings in the base and site-specific communities and a summary of thermal loads for space heating, cooling and domestic hot water are discussed in Section 9.1.

The characteristics of the conventional HVAC components (heating, ventilating, and air conditioning) are presented in this section. The type of equipment installed in the low-rise and townhouse residential buildings is representative of current engineering practices for meeting the heating and cooling requirements of these dwellings; however, the performance characteristics for the conventional components are representative of performance improvements projected for the 1985-1990 time frame, in which the HAHP-ICES is likely

to be used. The conventional components used in the office, retail, and high-rise structures are considered to be the most likely conventional components that the HAHP-ICES must compete with. HVAC components in the office building represent a conventional system applied to an energy conserving building design using the most appropriate technology to efficiently utilize heat recovery from internal cooling loads to serve the space heating requirements.

3.2.1 Conventional System Description—Low-Rise and Townhouse Apartments

Each dwelling is equipped with its own gas-fired furnace and central air conditioner with forced-air distribution. The forced-air furnace has a full-load efficiency of 75% and a seasonal efficiency of 65%. This seasonal efficiency value corresponds to conventional technology warm air furnaces, and use of the best current equipment to minimize cycling losses, such as automatic vent dampers and pilotless ignition systems. The vapor compression air conditioner is assumed to be a high-performance unit with a seasonal performance factor (COP) of 2.5. In the conventional case, each dwelling is also equipped with a 40-gallon, gas-fired water heater with a full load, steady-state efficiency of 70% and an annual efficiency of 55%.

In both the base and site-specific cases, the configuration of the HAHP-ICES is such that cooling is not provided to the low-rise and townhouse residences, but only to the office buildings (and high-rise and retail buildings, in the site-specific case), each low-rise and townhouse apartment still retains the conventional air conditioning system for the case of HAHP-ICES system operation. This maximizes convenience to the user and eliminates the need for a chilled-water distribution system. The central plant supplies hot water for domestic hot water to all residential dwelling units during the cooling season.

3.2.2 Conventional System Description — Office Building; Base Case

The following section discusses the characteristics of the heating/cooling systems in the 59,000 ft², six-story office building used in the base-case community load mix. Characteristics of the site-specific office building are discussed in Section 3.2.3, following the discussion of the characteristics of the HVAC components in the base-case office building.

The system consists of a nominal 140-ton heat reclaim chiller with double bundle condensers, three air handling units feeding variable volume air terminals, perimeter fan coil units fed by condenser water, hot-water storage, an electrical hot-water boiler and, finally, a water-cooling tower for rejecting unneeded heat. The selection of an electrical hot-water boiler over a gas or oil-fired unit is based on common industry practice.¹ In this particular case, the office building is equipped with an electrically-driven heat reclaim chiller; the electric hot-water boiler provides a backup function to the heat reclaim chiller. The electric hot-water boiler also supplies domestic hot water. Specification of characteristics of the conventional HVAC components are summarized in Table 3.7.

Table 3.7. CONVENTIONAL SYSTEM DESCRIPTION - OFFICE BUILDING; BASE CASE

1. Electric Motor Driven Reciprocating Compressor with Double Bundle Condenser
Carrier Reciprocating Chiller
Model 30 HH160
Electric Input (Summer) - 150.8 kW
Capacity (Summer) - 146.4 tons
Heat Rejected to Cooling Tower (Summer) - 189.3 tons
Leaving Water Temperature - 42°F
Entering Water Temperature - 52°F
Chilled Water Flow Rate - 351 gpm
Entering Condenser Water Temperature - 85°F
Leaving Condenser Water Temperature - 95°F
Condenser Water Flow Rate - 447 gpm

Rated Full Load Electric Input (Winter) - 172.8 kW
Rated Full Load Cooling Capacity (Winter) - 125 tons
Rated Full Load Heating Capacity (Winter) - 174 tons

Winter Cooling Load (percent of full load capacity as installed) - 55%
Winter Cooling Load (as installed) - 68.2 tons
Electric Input (Winter, as installed) - 79.5 kW
Winter Heating Capacity (as installed) - 90.8 tons
Rated Condensing Temperature - 126°F
Rated Send-Out Temperature - 120°F
Rated Return Temperature - 100°F
2. Electric Boiler
Coates Electric Boiler Model 24 HW-1
Efficiency - 100%
Electric Input - 330 kW
Capacity - 1.126×10^6 Btu/hr
3. Cooling Tower
Halstead and Mitchell Model GC KA 150
Capacity of 150 tons of refrigeration
95°F DB Ambient Temperature
78°F WB
85°F leaving water temperature
Two 5-hp fan motors
4. Thermal Storage Tank (Conventional System Only)
Storage Tank Volumetric Capacity - 10,000 gallons
Storage Tank Thermal Capacity - 2.4×10^6 Btu/hr
Storage Tank Temperature Swing - 30°F

Wintertime heat recovery and summer cooling is accomplished by a reciprocating heat reclaim chiller with two sets of condenser bundles. One set of bundles is piped to the building heating system. The other set of bundles is part of the cooling tower system and is open to the atmosphere. Since the interior or core of the building requires cooling year-round during operating hours, the heat removed by the refrigeration cycle and rejected by the condensers is made available to heat the perimeter. At a nominal condensing temperature of 129°F, the leaving water temperature would be about 118°F. Thus, the "fuel" for the heat reclaim system consists of those fixed cooling loads which are always present when the building is occupied, such as lights, people, and business equipment. The heat from these internal sources is removed by air side equipment, increased to a usable temperature level by the chiller and made available to the perimeter heating system. All operating modes of the conventional HVAC systems used in the base and site-specific cases are discussed in detail in Section 9.6.15.

The chiller uses four two-cylinder, semi-hermetic reciprocating compressors in two refrigerant circuits. Each compressor has cylinder unloading to provide a total of eight control steps to match changing load requirements. A temperature controller in the return chiller water piping controls a sequence step controller, which in turn, actuates switches to start or stop compressors and operates solenoid unloaders on the compressor cylinders in response to load changes.

The air handling units operate at a pressure of about 3 inches W.G. and consist of a forward curved fan section, a chiller water coil section, a bag filter section and a discharge damper section, which is controlled by a static pressure regulator to maintain a constant duct pressure. As the variable volume terminals will function properly at static pressure levels as high as 5 inches, the use of static pressure regulators prevents the possibility of noise generation should a few terminals be operating at high cubic feet/minute levels while the rest are closed. The static pressure sensors are located about one-third of the way down the main trunk line from each air handler.

The air handlers are used for cooling only with the chilled water coils controlled by discharge thermostats to maintain 55°F leaving air temperature. The cubic feet/minute of the units is directly proportional to the actual cooling load; thus, fan horsepower is reduced at reduced cooling levels.

The variable volume terminals are aerodynamically designed slot diffusers integrated into the ceiling T-bar system. Each terminal is capable of a maximum of 400 cubic feet/minute and may be operated as either a master or a slave unit. A master terminal uses a volume regulator, which is preset to the maximum cubic feet/minute required by the area served by the terminal and maintains desired air flow even though the duct pressure should change. A master terminal also incorporates a room thermostat, which samples room air by an aspiration principle and sets the terminal for the air flow necessary to maintain room conditions. The terminal is self-contained and operates off duct pressure; thus, it does not require any electrical or other control connections. One master unit may operate several slave units through interconnect control tubing. The master/slave functions may be changed by the addition or removal of the thermostat module.

The perimeter heating units are fan coil consoles connected to the heat reclaim system. Because the leaving water temperatures of the condenser is about 118°F, fan coils rather than convectors must be used. The fans are run constantly during the heating season and the water fed to them reset as the perimeter load varies with outside temperature. The fan coil units are sized to offset the perimeter loss at design winter conditions and provide a "neutral" interior zone, which will then be cooled by the VAV system.

The water cooling tower is a straight-forward, open-type unit, whose function is to reject system heat when it cannot be used by the perimeter system or stored in the water storage tank.

The electrical boiler provides heat below the system balance point, i.e., that point where the heat delivered by the chiller just meets the requirements of the perimeter heating system. The boiler is staged and its leaving water temperature is reset by an outside temperature sensor.

3.2.3 Conventional System Description — Office Building; Site-Specific Case

The office building in the site-specific case is treated as 2.1 base-case office buildings. Thus, in the site-specific case, the office building is centrally heated and cooled with two, 330 kW electric boilers interfacing with perimeter fan coil terminal units; and a 310-ton double-bundle, heat reclaim electric chiller interfacing with a variable air volume distribution system that serves the interior spaces of the building. During the winter, heat recovered from the interior spaces of the building is used to heat the perimeter of the building, and is supplemented, when necessary, by the electric boiler. Hot water is stored in a 20,000-gallon storage tank to reduce peak heating capacity requirements. Full- and part-load chiller performance is comparable to the 140-ton chiller used in the base-case office building.

3.2.4 Conventional System Description — High-Rise Apartments; Site-Specific Case

Each 104-unit high-rise building in the site-specific community is equipped with two, 35-hp gas boilers and a central electric chiller of 125-ton capacity. Boilers have a full-load efficiency of 83% and comparable part-load characteristics to the auxiliary boilers used in the central plant. Electric chiller full- and part-load performance characteristics were comparable to those of the nominal 140-ton Carrier reciprocating chiller used in the office building in the base case. A two-pipe system interfaces the central heating/cooling system with fan coils in each apartment. Each building has a central domestic hot water system fired with gas. Central domestic water heater efficiency is 83%.

3.2.5 Conventional System Description — Retail Store; Site-Specific Case

The 135,000 ft² retail store in the site-specific community is equipped with a 115-hp gas boiler and a 310-ton central electric chiller. The boiler has a full-load efficiency of 83% and comparable part-load characteristics to the auxiliary boilers used in the central plant. Electric chiller full- and

part-load performance characteristics were comparable to those of the nominal 140-ton Carrier reciprocating chiller used in the base-case office building. The heating and cooling system interfaces with a variable air volume distribution system. Domestic hot water is not provided in the retail store.

3.2.6 Comparison on Conventional and HAHP-ICES Performance Under Peak Heating and Cooling Load Conditions; Base and Site-Specific Cases

The peak heating mode performance of conventional components and HAHP-ICES for an ambient temperature of 30°F is evaluated using component performance characteristics. The peak cooling mode performance of conventional components and HAHP-ICES for an ambient temperature of 90°F is evaluated using appropriate component characteristics. Because both conventional and HAHP-ICES heating and cooling modes utilize a mix of components fueled by natural gas or electricity, to achieve a consistent measure of performance the overall community coefficient of performance (COP) has been based on the primary input requirements to distribute natural gas and to generate and distribute electricity. Overall community COP's are representative of relative performance of conventional heating and cooling components and HAHP-ICES.

Table 3.8 compares peak heating load performance of conventional components and the base case HAHP-ICES. Although HAHP-ICES outperforms conventional components, when the heat reclaim chillers in the office are used, the overall heating COP of 0.74 compares favorably to HAHP-ICES with internal heat source (COP = 0.82) and with outside air source (COP = 0.78). Table 3.9 shows that the conventional combination of efficient electric power generation and electric chillers (COP = 0.93) outperforms the base-case HAHP-ICES (COP = 0.88) in the cooling mode. Table 3.10 compares peak heating load performance of conventional components and HAHP-ICES in the site-specific case. HAHP-ICES outperforms conventional components, especially when the office heating load is served by an electric boiler (community COP = 0.65). When the office is equipped with a heat reclaim chiller, the conventional case COP of 0.77 is comparable to that of the HAHP-ICES. Table 3.11 compares the performance of conventional components and the site-specific HAHP-ICES in the cooling mode. The overall community cooling COP for the conventional components of 0.93 is comparable to the HAHP-ICES cooling COP which ranges from 0.92 with one steam turbine/heat pump unit in the central plant to 0.86 with four steam turbine/heat pump units in the central plant. A detailed breakdown of input/output characteristics of conventional components and base and site-specific HAHP-ICES is presented in Section 9.6.17.

3.3 Application of the HAHP-ICES to a Mixed-Load Community - Annual Performance Evaluation Methodologies

Based on the component characteristics described in the preceding section, methodologies were developed to evaluate the annual performance of both the conventional HVAC systems and the HAHP-ICES in terms of primary energy consumption.

Table 3.8. COMPARISON OF CONVENTIONAL AND HAHP-ICES (BASE CASE) PERFORMANCE UNDER PEAK HEATING LOAD CONDITIONS — AMBIENT TEMPERATURE 30°F

System Type	Total Community Peak Primary Energy Input ^a	Total Community Peak Heating Systems Output ^b	Overall Systems Community Heating COP Based On Primary Input ^c
	10 ⁶		
Conventional ^d	12.63	7.19	0.57
Conventional ^e	9.65	7.15	0.74
HAHP-ICES ^f	3.84	3.14	0.82
HAHP-ICES ^g	3.86	3.00	0.78

a. Primary energy input = $\frac{\text{Gas Input (Btu)}}{0.95} + \frac{\text{Electricity Input (Btu)}}{0.2968}$

HAHP-ICES values include pumping energy.

b. HAHP-ICES values = peak output — distribution losses.

c. Overall community heating systems COP =

$$\frac{\text{Output of all Heating and Hot Water Units}}{\text{Total Primary Energy}}$$

d. Assumes 100% of office building heat load from electric boiler; assumes no internal cooling load available to heat reclaim chiller.

e. Assumes an internal office cooling load of sufficient size to drive heat reclaim chiller to full load heat output. Electric boiler is not in use.

f. Assumes an internal cooling load available in office building to drive heat pump to full load heat output. Auxiliary gas boilers are also operating.

g. Assumes an external (ambient air) source for the heat pump. Auxiliary gas boilers are also operating.

Table 3.9. COMPARISON OF CONVENTIONAL AND HAHP-ICES (BASE CASE) PERFORMANCE
UNDER PEAK COOLING LOAD CONDITIONS — AMBIENT TEMPERATURE OF 90°F

<u>System Type</u>	<u>Total Community Peak Primary Energy Input^a</u>	<u>Total Community Peak Cooling Output</u>	<u>Overall Systems Community Cooling COP Based on Primary Input^b</u>
	<u>10⁶</u>		
Conventional	1.89	1.76	0.93
HAHP-ICES	2.42	2.13	0.88

a. Primary energy input = $\frac{\text{Gas Input (Btu)}}{0.95} + \frac{\text{Electricity Input (Btu)}}{0.2968}$

Values include cooling tower fan and pumping energy.

b. Overall community cooling systems COP =

$$\frac{\text{Output of all Cooling Systems}}{\text{Total Primary Energy}}$$

Table 3.10. COMPARISON OF CONVENTIONAL AND HAHP-ICES (SITE-SPECIFIC CASE)
PERFORMANCE UNDER PEAK HEATING LOAD CONDITIONS - AMBIENT TEMPERATURE OF 30°F

System Type	Total Community Peak Primary Energy Input ^a	Total Community Peak Heating Output ^b	Overall Community Heating COP Based on Primary Input ^c
	10^9		
Conventional ^d	3.68	2.40	0.65
Conventional ^e	3.11	2.40	0.77
HAHP-ICES ^f	2.06	1.53	0.74
HAHP-ICES ^g	2.06	1.51	0.73
HAHP-ICES ^h	1.81	1.39	0.77

a. Primary energy input = $\frac{\text{Gas Input (Btu)}}{0.95} + \frac{\text{Electricity Input (Btu)}}{0.2968}$

HAHP-ICES values include pumping energy.

b. HAHP-ICES values = peak output - distribution losses.

c. Overall community heating systems COP =

$$\frac{\text{Output of all Heating and Hot Water Units}}{\text{Total Primary Energy}}$$

d. Assumes 100% of office building heat load from electric boiler; assumes no internal cooling load available to heat reclaim chiller.

e. Assumes an internal office cooling load of sufficient size to drive heat reclaim chiller to full load heat output. Office electric boiler not in operation.

f. Assumes one steam turbine/heat pump unit in the central plant. Assumes an internal cooling load available in office building to drive heat pump to full load heat output. Gas boilers are also operating.

g. Assumes one steam turbine/heat pump unit in the central plant. Assumes an external (ambient air) source for the heat pump. Gas boilers are also operating.

h. Assumes four steam turbine/heat pump units in the central plant. In the four steam turbine/heat pump unit case, one steam turbine produces electricity (reducing purchased electricity requirements) with only steam turbine condenser heat available. It is assumed that the remaining three steam turbine/heat pump units operate with external (ambient air) heat source. Gas boilers are also operating. Includes credit for electricity produced.

Table 3.11. COMPARISON OF CONVENTIONAL AND HAHP-ICES (SITE-SPECIFIC CASE)
PERFORMANCE UNDER PEAK COOLING LOAD CONDITIONS - AMBIENT TEMPERATURE OF 90°F

System Type	Total Community Peak Primary Energy Input ^a	Total Community Peak Cooling Output	Overall Systems Community Cooling COP Based on Primary Input ^b
	10^7		
Conventional	1.61	1.49	0.93
HAHP-ICES ^c	1.12	1.03	0.92
HAHP-ICES ^d	1.20	1.03	0.86

a. Primary energy input = $\frac{\text{Gas Input (Btu)}}{0.95} + \frac{\text{Electricity Input (Btu)}}{0.2968}$

Values include cooling tower fan and pumping energy.

b. Overall community cooling systems COP =

$$\frac{\text{Output of all Cooling Systems}}{\text{Total Primary Energy}}$$

c. Assumes only one steam turbine/heat pump unit plus electric chillers.

d. Assumes four steam turbine/heat pump units plus electric chillers.

3.3.1 Methodology — Conventional System Performance Evaluation; Base and Site-Specific Cases

Hourly thermal loads imposed on HVAC equipment were generated for all building types (office, retail, low-rise, townhouse, and high-rise) using the Meriwether Code. Thermal loads for the office and retail buildings were simulated using hourly weather data and hourly schedules for occupation and machinery operation. The annual performance of the conventional system as applied to the low-rise and townhouse buildings was developed with constant seasonal performance factors describing HVAC component performance. Annual performance of the conventional systems applied to the high-rise apartment building and to the retail store and was determined by using hourly thermal load data and the Meriwether Code. The detailed component characteristics of the conventional HVAC equipment installed in the office building were supplied by R.G. Fleischman Co. and the Trane Co. Consolidated Natural Gas utilized an equipment simulation program developed in-house to generate the annual performance of the conventional equipment in the base and site-specific office buildings.

3.3.2 Methodology — HAHP-ICES Performance Evaluation; Base and Site-Specific Cases

A computer code has been written to aid in the analysis of the annual performance of the HAHP-ICES. Analysis was done for 8760 hours of thermal load data. The corresponding performance of the HAHP-ICES, as a function of load and ambient temperature, was then applied to each hourly load to find the consumption of gas and electricity by the heat pump system. Energy consumption figures include pumping and cooling tower fan loads. Thermal losses from the thermal distribution system were not explicitly calculated in the computer code. Distribution system thermal losses were determined by separate calculation on an annual basis and their impact on HAHP-ICES primary energy consumption determined. The methodology for calculation of distribution system thermal losses is reported in Section 9.6.5.3. A control philosophy was developed to guide in the running of the machine in a load-following configuration, with the purpose of minimizing heat wasted by the system.

The control philosophy for operation of HAHP-ICES in the base case is set forth in Table 3.12, and the control philosophy for operation of HAHP-ICES in the site-specific case is set forth in Table 3.13.

Some specific features of the control philosophy used in the operation of HAHP-ICES in the site-specific case should be noted. In the site-specific case, if only one turbine is used, it may be operated in one of three modes during the heating season:

1. If an internal cooling load is available, it will heat pump from that heat source, modulating the turbine and compressor to follow the cooling load;
2. Where there is no internal cooling load or the cooling load is less than 30% of the module's capacity, it will outside-air-source heat pump, modulating the turbine and compressor to follow the heat load;

Table 3.12. HAHP-ICES CONTROL PHILOSOPHY — BASE CASE

- I. General Rule: System follows load so that only in the cooling mode is heat rejected to the cooling tower
- II. Heating mode with ambient temperature less than 30°F*
 - A. Internal heat pumping available
 1. Limit amount of heat pumped to equal office heat load
 - a. If office heat load is greater than internal pumped heat available, supplemental heat comes directly from boiler.
 - b. If office heating load is less than internal pumped heat available, then excess turbine shaft power is available for production of electricity to help satisfy HVAC parasitics, under the restrictions that:
 1. A load exists for the associated turbine heat
 2. The electricity can be consumed on-site for HVAC parasitics
 3. The amount of electricity produced is at least 5 kW
 2. Turbine condenser heat is used to help satisfy the residential heat load
 - a. If turbine condenser heat exceeds residential heating load, turbine shaftpower output is limited such that the sum of pumped heat and turbine condenser heat equals the total office building heat load and the residential heat load
 - b. If turbine condenser heat is less than the residential heat load, additional heat is supplied directly from the boiler.
 3. See Item V
 - B. External heat pump when internal cooling load not available. Follow same operating rules as for internal heat pumping case.
 - C. If heat pumping not available, produce electricity following Rule II, A, 1, b, and meet additional heat load with boiler.
- III. Heating mode with ambient temperature greater than 30°F
 - A. In this mode, pumped heat can be added to the residential heating heating thermal distribution loop with the limitation that the return water temperature may be increased by only 5°F by refrigerant condenser heat. The upper limit on pumped heat imposed by this constraint is the sum of the office building heat load plus a percentage of the residential heat load. This percentage is 20% at an ambient temperature of 30°F, increasing to 25% at 50°F.
 - B. Overall operation is guided by the same control philosophy as for ambient temperatures less than 30°F.
- IV. Cooling load with ambient temperature greater than 70°F
 - A. Operate turbine driven chiller first. Meet additional cooling load with electrically driven chiller. If cooling load is less than turbine driven chiller maximum output, generate electricity following Rule II, A, 1, b. In all cases, use turbine condenser heat to meet residential heating load which during cooling season consists of the office and residential domestic hot water load. Refrigerant condenser heat and excess turbine condenser heat is rejected at the the cooling tower.
- V. Cooling load with ambient temperature less than 70°F
 - A. The cooling load remaining above internal heat pumping cooling capacity is met with outside air ventilation up to the limit of the office building's 60,000 CFM/min air handlers. Any additional cooling load is met with the turbine driven chiller. Excess refrigerant condenser heat and turbine condenser heat is rejected at the cooling tower.

* Because refrigerant condenser heat is at a relatively low temperature, only office heating loads can be served by pumped heat when ambient temperature is less than 30°F. Office is equipped with fan coils which can utilize lower temperature heat than baseboard units used in residences.

Table 3.13. CONTROL PHILOSOPHY — SITE-SPECIFIC CASE

- I. General Rule: System follows load so that only in the cooling mode is heat rejected to the cooling tower.
- II. Heating Mode*
 - A. If internal heat pumping is available
 - 1. Use at least one turbine-driven unit in the internal heat pump mode and additional units as necessary up to the total units less one.
 - 2. Use one turbine to generate electricity for pumping loads
 - 3. Use any remaining turbine-driven units in external heat pump mode as necessary
 - 4. Meet additional heat requirements with boilers
 - B. If internal heat pumping is not available
 - 1. Use one turbine-driven unit in external heat pump mode
 - 2. Use one turbine to generate electricity for pumping loads
 - 3. Use remaining turbine-driven units in external heat pump mode as necessary
 - 4. Meet additional heat requirements with boilers
- III. Cooling Mode
 - A. Use turbine-driven units in cooling mode as necessary
 - B. If all turbines are not in use for cooling, generate electricity for pumping loads
 - C. Meet additional cooling loads with auxiliary cooling units
 - D. If heating load (DHW) is greater than turbine condenser heat available, meet additional heating load with boilers.

* In both internal and external heat pump modes, the limit on total pumped heat usable by the system (assuming heat source or number of turbines do not impose a limit) is equal to:

- at ambient temperature less than 30°F — the office space heating load
- at ambient temperature above 30°F — the office space heating load plus a percentage of the high temperature heating loads. This percentage is 20% at a 30°F ambient, increasing to 25% at 50°F.

3. When there is a low heat load, the turbine will drive the generator to produce electricity as long as the generator load is such that the turbine is loaded to at least 30% of its full load output.

When more than one turbine is used, only one turbine is used to generate electricity, and this turbine does not have outside air source heat pumping capabilities. The remaining turbines can use outside air or internal heat recovery as a heat source, but they follow the load and do not produce excess horsepower beyond the compressor requirement.

3.4 Application of HAHP-ICES to a Mixed-Load Community - Annual Performance Evaluation; Base Case

The annual metered- and primary-energy consumption by both the conventional HVAC and the HAHP-ICES were developed for the base case of Chicago climate. HAHP-ICES energy consumption figures include distribution pumping and cooling tower fan loads. Distribution pumping and cooling tower pumping and fan loads were determined explicitly in the computer code written to analyze the annual performance of the HAHP-ICES. Losses from the HAHP-ICES thermal distribution system were determined by separate calculation on an annual basis and are reflected in the results presented for HAHP-ICES primary energy consumption. The rationale for selection of the mixed-load community is presented in Section 3.4.1. The results of the analysis are presented in Section 3.4.2. In addition, the sensitivity of metered- and primary-energy consumption to climate was explored for the cities of Minneapolis, Kansas City, and Atlanta. The results are presented in Section 3.4.3. The impact of load mix on metered- and primary-energy consumption was also explored using Chicago weather, and the results are discussed in Section 3.4.4.

3.4.1 Selection of Mixed-Load Community - Base Case

In the base case, the load applied to the system was developed such that both heating and cooling loads generally exceeded the unit's full-load capacity. Thus, the HAHP-ICES tended to operate at near-to-peak performance, with loads in excess of its capacity supplied by conventional components.

The base-case, mixed-load community consists of one six-story office building with 59,000 ft² of floor space and a year-round internal cooling load, and five low-rise apartment buildings, each with 24 units.

3.4.2 Annual Performance - Metered- and Primary-Energy Consumption - Chicago Weather - Base Case

The annual metered- and primary-energy consumption by both the conventional HVAC systems and the HAHP-ICES using Chicago weather conditions are summarized in Table 3.14.* The HAHP-ICES displaces 10.5 million CF of natural gas and 415,000 kWhr of electric power that would have been used by the conventional systems to supply heating and cooling to the mixed-load community. The

* Chicago's weather for 1952 was used in the evaluation. The weather for the year 1952 is within 56 degree-days for both the heating and cooling seasons for the average between the years 1949 and 1957.

Table 3.14. METERED- AND PRIMARY-ENERGY CONSUMPTION OF BASE CASE
CONVENTIONAL AND HAHP-ICES SYSTEMS - CHICAGO WEATHER

<u>Metered-Energy</u>	<u>Baseline Conventional</u> ^a	<u>HAHP-ICES</u>
Gas, 10 ³ CF/yr	10,450	9,022
Electricity, kWhr/yr	414,600	93,790
<u>Primary-Energy</u>		
Gas, 10 ⁹ Btu/yr	11.19	9.663
Resources used to generate electricity, 10 ⁹ Btu/yr	4.768	1.079
Gas ^b to make up distribution system thermal losses, 10 ⁹ Btu/yr		<u>0.468^c</u>
Total	15.96	11.21 ^d

^a Energy consumption which is displaced when HAHP-ICES is used.

^b Heat loss from thermal distribution system made up by 83% efficient boiler.

^c Heat loss from thermal distribution system is 4.17% of total primary energy consumption. Thermal losses were 3.688×10^8 Btu/yr or 6.15% of the total low-rise thermal load for space heat and domestic hot water.

^d Primary energy reduction = 29.8%.

HAHP-ICES consumes 9.5 million CF of natural gas and 94,000 kWhr of electricity (including gas energy required to make up thermal distribution system heat losses).

Primary energy consumption by both systems was computed using efficiencies of 95% for gas production and transmission, and 29.68% for electricity generation and distribution. The HAHP-ICES displaces 11×10^9 Btu of primary energy used for electricity generation, for a total displacement of 15.96×10^9 Btu of primary energy. Before heat losses from the thermal distribution system are accounted for, the HAHP-ICES consumes 9.7×10^9 Btu of natural gas primary energy and 1.1×10^9 Btu of primary energy used for central electric power generation. If the heat loss from the thermal distribution system serving the low-rise buildings (the central plant is housed in the office building) of 3.688×10^8 Btu/yr (6.15% of the total low-rise thermal load for space heat and domestic hot water) is made up by an 83% efficient natural gas-fired boiler, the additional primary energy of 4.677×10^8 Btu/yr results in a total primary energy consumption of 11.21×10^{10} Btu/yr by HAHP-ICES. Thermal losses, thus, amount to 4.17% of total HAHP-ICES primary energy consumption; and the HAHP-ICES has a primary energy consumption of 29.8% less than that of the conventional HVAC system.

3.4.3 Impact of Geographic Location on Annual Metered- and Primary-Energy Consumption in the Base Case

This area of sensitivity analysis evaluated the impact of various heating and cooling loads intrinsic to different geographic locations on the performance of HAHP-ICES as measured by reductions in primary-energy use compared with a conventional HVAC system. The four geographic locations selected for this analysis were Chicago (base-case city, midwest); Minneapolis (north); Kansas City (midwest); and Atlanta (southeast). The selected cities and their geographic locations, their climate regions, and their seasonal-degree-day totals for heating and cooling are given in Table 3.15. To make a meaningful comparison of the HAHP-ICES performance in different climates, an adjustment was made in the relative size of the office building to put its cooling load on a comparable basis with the base-case city of Chicago. For the office building, the peak air-conditioning requirement for each selected city was compared with that of Chicago. Because the air-conditioning capacity of the HAHP-ICES is fixed in the computer simulation, the size of the office building was adjusted to result in the same peak cooling load as in the base-case city. For simplicity, domestic hot water loads were based on Chicago water temperatures. As may be seen in Section 9.2, Summary of Thermal Loads, the difference in actual domestic hot water loads for Minneapolis, Kansas City, and Atlanta from those for Chicago are slight, on the order of a reduction of less than 8.0%. All other variables were held constant with respect to the base case.

The sensitivity to geographic location of metered- and primary-energy consumption of conventional HVAC systems and the HAHP-ICES is presented in Table 3.16. Primary-energy use for both systems decreases as the climate becomes milder; there is also a dramatic change in the percentage reduction in primary-energy use as the climate becomes milder. Minneapolis, with nearly 8000 heating-degree-days, shows a reduction of 32% in primary-energy use when using a HAHP-ICES. As seen in the previous section, Chicago, with 6500 heating-degree-days, saves nearly 33%.

Table 3.15. CLIMATIC CHARACTERISTICS OF GEOGRAPHIC LOCATIONS IN WHICH
BASE CASE CONVENTIONAL AND HAHP-ICES SYSTEMS WERE EVALUATED

<u>City</u>	<u>Minneapolis</u>	<u>Chicago</u>	<u>Kansas City</u>	<u>Atlanta</u>
Geographic Location	North	Midwest	Midwest	Southeast
Census Region	West North Central	East North Central	West North Central	South Atlantic
Climate Region	Temperate Continental (Cool Summer)	Temperate Continental (Warm Summer)	Temperate Continental (Warm Summer)	Humid (Subtropical)
Size of Office Building Relative to Base Case*	1.4	1.0	0.86	0.91
Number of Degree-Days Annually (Year)	HDD = 7997.1 CDD = 674.0 (1956)	HDD = 6506.4 CDD = 809.8 (1952)	HDD = 4811.6 CDD = 1609.0 (1957)	HDD = 2827.3 CDD = 1717.6 (1955)
Average Degree-Days	HDD = 7964.3 CDD = 704.6	HDD = 6557.5 CDD = 753.9	HDD = 4849.3 CDD = 1686.7	HDD = 2825.6 CDD = 1717.3
Time Period	(1955-1964)	(1949-1957)	(1949-1958)	(1949-1958)

* The base case is Chicago climate. The size of the office buildings was adjusted to result in the same peak cooling load as the base case Chicago office building of 59,000 square feet.

Table 3.16. METERED- AND PRIMARY-ENERGY CONSUMPTION OF BASE CASE
CONVENTIONAL AND HAHP-ICES SYSTEMS - SENSITIVITY TO GEOGRAPHIC LOCATION

	Minneapolis		Chicago		Kansas City		Atlanta	
	Conventional ^a	HAHP-ICES	Conventional ^a	HAHP-ICES	Conventional ^a	HAHP-ICES	Conventional ^a	HAHP-ICES
<u>Metered-Energy^b</u>								
Gas, 10 ³ CF/yr	12,494	11,146.49	10,447.56	9,022.29	8,980.5	7,948.69	6806.5	6466.79
Electricity, kWhr/yr	540,283	118,654.37	414,620	93,793.5	250,161	100,502.06	253,311.69	122,893.06
<u>Primary-Energy</u>								
Gas, 10 ⁹ Btu/yr ^c	13.4146	11.9678	11.189	1.6628	9.6422	8.5344	2.3080	6.9433
Electricity, 10 ⁹ Btu/yr ^d	6.2129	1.3646	4.7678	1.0785	2.8767	1.1557	2.9129	1.4132
Total, 10 ⁹ Btu/yr	19.6275	13.3324	15.9569	10.7414	12.5189	9.6901	10.2209	8.3565
Primary-Energy Reduction, %	--	32.1	--	32.8	--	22.6	--	18.2

^a Energy consumption which is displaced when the HAHP-ICES is used.

^b Values include distribution pumping and cooling tower pumping and fan loads; distribution system thermal losses are not included.

^c Gas energy at 1020 Btu/CF. Gas production and transmission efficiency = 95%.

^d Electricity generation and distribution efficiency = 29.68%.

But savings are reduced to only 23% in Kansas City, with 4800 heating-degree-days, and 18% in Atlanta, with 2800 heating-degree-days. The results of the sensitivity analysis of primary-energy saving as a function of climate indicate that the HAHP-ICES favors geographic locations that provide a heating load of sufficient duration to maximize the benefits of HAHP-ICES energy efficiency potential in the heat pumping mode, where its overall heating COP is greater than that of conventional heating systems. Clearly, increased cooling load requirements do not improve the HAHP-ICES performance, particularly because its overall cooling COP on a primary source basis of 0.84 (0.88×0.95) is inferior to that of a conventional electric chiller, 1.21 (4.1×0.2968), due to the lower efficiency of the HAHP central plant steam turbine. However, if additional heating and domestic hot water loads were added via more residential units, the base-case load mix could be re-established and more favorable energy savings would result.

3.4.4 Impact of Load Mix on Annual Metered- and Primary-Energy Consumption

The configuration and design of the HAHP-ICES central plant discussed in this report is based, to a large extent, upon the loads presented to the plant by the community. The loads examined in the base case result from a community mix of one office building and five low-rise apartment buildings. As the community mix of buildings changes, obviously, the load mix or thermal demands on the central plant varies. It is appropriate to mention, at this juncture, that the effects of changes in the community mix of buildings are analyzed and discussed in Section 6 from the viewpoint of community growth or contraction. The results from that analysis are equally applicable when viewed as the effect of changes in a community's load mix or thermal demands.

The analysis reveals that compared to conventional HVAC systems, the HAHP central plant's superior performance is relatively insensitive to loads with higher heating season demands than those contained in the base case. Load mixes, for whatever reason, which demand heat during the cooling season, increase the HAHP annual performance advantage over the conventional system. Conversely, load mixes which demand summertime cooling, but little heating, cause the central plant's performance to be considerably degraded from that exhibited in the base case.

The key to the load mix effect on central plant base-case performance lies in the domestic hot water demands, a year-round heating load. For a concept which is heat-actuated, this thermal load is necessary in order for the annual performance advantage to remain large. It is suggested, therefore, that as Section 6 is read, it be viewed from both a growth and load mix standpoint.

3.5 Application of the HAHP-ICES to a Mixed-Load Community - Annual Performance Evaluation - Site-Specific Case

Based on the component performance characteristics described in the preceding sections, the annual performance of both the conventional HVAC and the HAHP-ICES were developed in terms of primary-energy consumption. HAHP-ICES energy consumption figures include distribution pumping and cooling tower pump and fan loads. These loads were determined explicitly in the computer code written to analyze the annual performance of the HAHP-ICES. Losses occurring

during the distribution of hot and chilled fluids by the HAHP-ICES thermal distribution system were determined by a separate calculation on an annual basis and are reflected in the results presented for HAHP-ICES primary energy consumption.

Pittsburgh weather for 1961 was used in the evaluation of the site-specific case.

3.5.1 Selection of Mixed-Load Community - Site-Specific Case

In the base case, the load applied to the system was developed such that both heating and cooling loads generally exceeded the unit's full-load capacity. Thus, the HAHP-ICES tended to operate at near-to-peak performance, with loads in excess of its capacity supplied by conventional components.

The site-specific community was not developed with the philosophy of base-loading the central plant, rather a community was selected corresponding to a realistic mix of building types. The site-specific community consists of an office building of 124,000 ft² floor area, retail space with 135,000 ft² of floor area, 520 units of high-rise dwellings, 120 low-rise dwelling units, and 42 townhouse units.

3.5.2 Annual Performance - Primary-Energy Consumption; Site-Specific Case

Primary-energy consumption by both conventional HVAC and the HAHP-ICES in the site-specific case were developed using Pittsburgh weather for 1961. Using efficiencies of 95% for gas production and transmission, and 29.68% for electricity generation and distribution, the conventional HVAC systems use a total of 74.2×10^9 Btu/yr of primary energy that may be displaced by the use of HAHP-ICES. The breakdown of primary-energy use by the conventional HVAC systems is shown in Table 3.17. Conventional HVAC systems consume a total of 58.0×10^9 Btu/yr of primary gas energy and 16.2×10^9 Btu/yr of primary resources used to generate electricity.

Table 3.17. PRIMARY ENERGY USED BY CONVENTIONAL HVAC SYSTEMS THAT MAY BE DISPLACED BY HAHP-ICES (10^6 Btu/yr); SITE-SPECIFIC CASE

<u>Building Type</u>	<u>Gas</u>	<u>Resources Used To Generate Electricity</u>	<u>Total</u>
Office	0	11,770	11,770
Retail	7,110	2,200	9,310
High-Rise	35,410	2,270	37,690
Low-Rise	10,810	0	10,810
Townhouse	<u>4,640</u>	<u>0</u>	<u>4,640</u>
Total	57,970	16,250	74,220

Primary energy consumption by HAHP-ICES as a function of the number of turbines in the central plant is presented in Table 3.18. The energy required to offset the thermal losses from the HAHP-ICES thermal distribution system must be added to primary-energy use by the HAHP-ICES for heating and cooling. Thermal losses from distribution of hot fluids for space heating and domestic hot water were 1.728×10^9 Btu/yr, or 4.2% of thermal loads for space heating and domestic hot water. To make up thermal losses with an 83% efficient gas-fired boiler, primary energy required was 2.192×10^9 Btu/yr. Thermal gains during distribution of chilled fluids for space cooling were 7.960×10^6 Btu/yr, or 0.1% of thermal loads for space cooling. To make up thermal gains with a gas-fired, steam turbine-driven chiller with an assumed COP of 0.88, primary energy required was 9.522×10^6 Btu/yr. Total primary-energy use required to offset thermal losses from the HAHP-ICES thermal distribution system was 2.20×10^9 Btu/yr. The case with zero turbines may be regarded as a comparison of HAHP-ICES to a conventional district heating system with 83% efficient boilers and efficient central chillers. Thus, an efficient district heating system could reduce primary energy consumed in a community by 8.5%. The introduction of a HAHP-ICES produces considerably more savings of primary energy, ranging from 15.4% with only one turbine, up to 21.5% with four turbines. Note that a maximum of four turbines was used in the central plant because beyond this number, the resultant system surplus was estimated to be insufficient to defray the life cycle cost of the thermal distribution system. Looking at the detailed breakdown of primary-energy consumption, primary energy required to offset thermal losses from the HAHP-ICES thermal distribution system range from 3.2% to 3.8% of total primary energy use for zero to four turbines, respectively. The use of HAHP-ICES results in a dramatic reduction of primary energy used for electricity production — 81% with four turbines; electricity being used mainly for cooling production in conventional systems, with this electricity being displaced by the gas-fired, steam engine-driven chiller in the HAHP-ICES. The reduction of primary gas usage as compared with the conventional system is not so dramatic — 8.5% with four turbines — mainly attributable to the fact that some of the primary energy for electricity production is now used in a boiler for the steam turbine prime movers in the HAHP-ICES. In terms of a reduction of consumption of crude oil, at 5.8×10^6 Btu/bbl, a HAHP-ICES with four turbines reduces consumption of crude oil by 2748 bbl/yr.

3.6 First- and Second-Law Analysis of HAHP-ICES and of Conventional Systems

An analysis was performed on the thermodynamics of the HAHP-ICES base and site-specific concepts in both heating and cooling modes. A first- and second-law analysis was also performed for a conventional gas-fired furnace and a conventional electric chiller. The first- and second-law analyses cover both annual performance and performance under average load conditions. The analysis of first- and second law performance evaluation under average load conditions is applicable to both base and site-specific HAHP-ICES and conventional systems. The first law analysis traces the flow of energy through the system from fuel input at the source (gas field or electric power plant) to the thermal outputs of the thermal distribution system. However, the first-law analysis does not indicate the most efficient manner in which to utilize the energy input to the system. The concept of thermodynamic availability as embodied in the second-law analysis provides a means to technically evaluate processes in their comparative efficiency for the utilization of energy.

Table 3.18. PRIMARY-ENERGY CONSUMPTION AND REDUCTION IN PRIMARY-ENERGY CONSUMPTION BY HAHP-ICES; SITE-SPECIFIC CASE

Number of Turbines	Primary Energy Consumption, 10^6 Btu/yr			Total Primary Energy Use, 10^6 Btu/yr	Reduction Over Conventional,** %	Thermal Loss,† %
	Gas	Resources Used To Generate Electricity	Gas Used To Offset Thermal Losses *			
0	55290	10430	2200	67920	8.5	3.2
1	53940	6640	2200	62780	15.4	3.5
2	54350	5000	2200	61550	17.1	3.6
3	53450	3880	2200	59530	19.8	3.7
4	53050	3030	2200	58280	21.5	3.8

* Thermal losses during distribution of hot fluids were 1.728×10^9 Btu/yr, or 4.2% of thermal loads for space heating and domestic hot water. To make up thermal losses with an 83% efficient gas-fired boiler, primary energy required was 2.192×10^9 Btu/yr. Thermal gains during distribution of chilled fluids were 7.960×10^6 Btu/yr, or 0.1% of thermal loads for space cooling. To make up thermal gains with a gas-fired, steam turbine-driven chiller with an assumed COP of 0.88, primary energy required was 9.522×10^6 Btu/yr.

** Primary energy consumption, conventional = $74,220 \times 10^6$ Btu/yr.

† As a percentage of total primary energy use, including thermal losses.

Thermal loads from the distribution system of HAHP-ICES were not explicitly considered in the performance analyses. The impact of an assumed loss of 15% of the distributed thermal energy from the HAHP-ICES base-case hot water distribution system on first- and second-law annual performance and heating mode performance was evaluated. These results are representative of the impact that losses from the thermal distribution system in the site-specific case would have on the thermodynamics of HAHP-ICES in its site-specific configuration.

In the following sections, the results of first- and second-law analyses are presented.

3.6.1 First-Law Analysis

The first-law analysis follows energy flows from input at the inlet of the gas pipeline or electric power plant to the burner of the steam boiler or the gas furnace, to the thermal output at the heat pump condenser and turbine condenser, and subsequent thermal output to the thermal distribution system. The theoretical performance of the systems under average load conditions as if heat engines operated at their potential Carnot efficiencies and without frictional losses, along with the performance of practical machinery, is presented. Thus, actual systems may be compared as to their performance in theory, at least from the standpoint of the first law of thermodynamics. Systems are also compared as to how well they perform in practice on both annual and average load bases.

3.6.1.1 Annual Performance — Base Case

Annual first-law performance of the base-case conventional system is presented in Figure 3.1; annual first-law performance of the base-case HAHP-ICES is presented in Figure 3.2. Note that in both cases, the basis is 100 units of primary energy input and that parasitic loads, such as cooling tower fans and pumps, are included in the primary input to the systems. HAHP-ICES distribution system heat losses are not explicitly considered. Examining Figures 3.1 and 3.2, it is clear that the HAHP-ICES is able to provide more cooling, space heating, and domestic hot water than a conventional system. In this case, HAHP-ICES is able to provide nearly 50% more thermal services for each unit of primary energy input than the conventional system. This results from the use of pumped heat, heat recovery from the steam turbine condenser, and efficient boilers. By contrast, residential furnaces and domestic water heaters are significantly less efficient in providing thermal energy for space heating and cooling, and although the office building uses an electric heat pump for space heating, backup energy is an electric resistance heated boiler which consumes much more primary energy than the 83% efficient backup boilers used in the HAHP-ICES.

The impact of thermal losses in the base-case HAHP-ICES hot water distribution system is to reduce the quantity of thermal services provided per unit of primary energy. As an example, if 15% of the thermal energy supplied for space heating and domestic hot water must be made up by the backup boiler at 83% efficiency, the additional primary-energy use reduces space cooling per 100 units of primary energy from 32 units without losses to 29 units when losses

1. Estimated Seasonal Performance Factor - Cooling = 3.811. Assumes average conditions of 90°F ambient, 80% load, 91% efficient motor and full- and part load performance comparable to steam turbine-driven chiller.
2. Residential only, all office space heating and domestic hot water (DHW) loads are met with electrically-powered equipment; no on-site flue losses.
3. Assumed space heating and DHW seasonal performance factor for residential gas-fired furnaces and water heaters = 0.6.

Figure 3.1. NORMALIZED ANNUAL FIRST-LAW ANALYSIS — BASE CASE CONVENTIONAL SYSTEM

BASIS: 100 Units of Source Energy Input

Heat Supplied
To
Conditioned Space
 $E = 39.85$

Heat Removed
From
Conditioned Space
 $E = 32.21$

DHW Supplied
 $E = 28.77$

Low Temperature Heat
Rejected During Cooling
Season to Cooling Tower
from Turbine Driven Chiller
and Back Up Chiller Condensers
 $E = 24.95$

High Temperature Turbine Condenser
Heat Rejected to Cooling Tower
 $E = 3.165$

Boiler Flue Loss¹
 $E = 14.52$

Primary
Gas
 $E = 89.96$

Primary
Electricity
 $E = 10.04$

Base Case HAHP-ICES

TOTAL
PRIMARY
ENERGY:
100 UNITS

1. Based on 83% efficient primary and supplemental boilers and primary gas input.

Figure 3.2. NORMALIZED ANNUAL FIRST-LAW ANALYSIS — BASE-CASE HAHP-ICES

are considered; space heating is reduced from 40 to 36 units and domestic hot water from 29 to 26 units. Even with thermal losses of 15%, HAHP-ICES still provides more thermal services per unit of primary energy input than does the conventional system.

3.6.1.2 Annual Performance — Site-Specific Case

Annual first-law performance of the site-specific conventional system is presented in Figure 3.3, annual first-law performance of the site-specific HAHP-ICES is presented in Figure 3.4. Note that in both cases the basis is 100 units of primary energy input and that parasitic loads, such as cooling tower fans and pumps, are included in the primary input to the systems. HAHP-ICES distribution system heat losses are not explicitly considered. Examining Figures 3.3 and 3.4, it is clear that the site-specific HAHP-ICES is able to provide more cooling, space heating, and domestic hot water than a conventional system. This results from the use of pumped heat, heat recovery from the steam turbine condenser, and efficient boilers.

3.6.1.3 Heating Mode — Average Load Conditions

First-law performance under average load conditions for conventional and HAHP-ICES is shown in Figures 3.5 and 3.6. These results are equally applicable to HAHP-ICES and conventional base and site-specific configurations. First-law performance of the conventional and heat pump systems is at an ambient temperature of 30°F. The conventional gas furnace supplies thermal energy to the distribution system with a source basis overall COP of 0.67. A practical heat pump system supplies thermal energy with an overall COP of 1.17. Overall COP's do not include parasitic pumping or cooling tower fan loads nor HAHP-ICES distribution losses. By contrast, the theoretical performance of a heat pump operating with a Carnot efficiency of 0.68 for the turbine (turbine efficiency = 0.28, in practice), suffering no gearbox losses, and with a heat pump COP of 91 (COP is only 3.30 in practice) due to the absence of temperature differences across its heat exchangers, could have an overall COP of 49.0. In the heating mode, the heat pump outperforms the conventional gas furnace on a first-law analysis basis.

The impact of a HAHP-ICES thermal distribution loss of, for example, 15%, is to reduce the heating COP from 1.17 to 0.99.

3.6.1.4 Cooling Mode — Average Load Conditions

First-law performance under average load conditions for conventional and HAHP-ICES is shown in Figures 3.7 and 3.8. First-law performance of the conventional and heat pump systems is at an ambient temperature of 90°F. A practical, conventional electric chiller supplies chilled water to the conditioned space with a COP of 1.11 on a source basis. In theory, the overall COP could be 29.63. In the cooling mode, the heat pump has a practical overall COP of 0.84. Overall COP's do not include parasitic pumping or cooling tower fan loads, nor HAHP-ICES distribution losses. The theoretical overall COP of the heat pump is 18.01. In the cooling mode, it is clear that a conventional chiller outperforms the heat pump. The reason is the greater overall efficiency of electric power generation and transmission in a central plant of 29.68%,

1. Estimated Seasonal Performance Factor - Cooling = 3.811. Assumes average conditions of 90°F ambient, 80% load, 91% efficient motor and full and part load performance comparable to steam turbine-driven chiller.
2. Residential only, all office space heating and domestic hot water (DHW) loads are met with electrically powered equipment; no on-site flue losses.
3. Assumed space heating and DHW Seasonal Performance Factor for retail and residential gas-fired furnaces and water heaters = 0.6.

Figure 3.3. NORMALIZED ANNUAL FIRST-LAW ANALYSIS — SITE-SPECIFIC CONVENTIONAL SYSTEM
(Basis: 100 Units of Source Energy Input)

1. Based on 83% efficient primary and supplemental boilers and primary gas input.

Figure 3.4. NORMALIZED ANNUAL FIRST-LAW ANALYSIS — SITE-SPECIFIC HAHP-ICES
FOUR HEAT PUMP UNITS (Basis: 100 Units of Source Energy Input)

Basis: 100 Units of Source Energy Input; Ambient Temperature = 30°F

Overall Heating COP; Source Basis = 0.67

Overall Heating COP; Input to Boiler Basis = 0.70

E^1 = Energy units flowing through system.

Adiabatic flame temperature assumed to be 2700°F.

Figure 3.5. FIRST-LAW ANALYSIS — CONVENTIONAL GAS-FIRED FURNACE; AVERAGE LOAD CONDITIONS

Basis: 100 Units of Source Energy Input

Overall Heating COP, Source Basis 49.04 (Theory)
1.17 (Practice)

Overall Heating COP, Input to Boiler Basis 51.62 (Theory)
1.23 (Practice)

Figure 3.6: FIRST-LAW ANALYSIS — HAHF CENTRAL PLANT — HEATING MODE WITH INTERNAL HEAT RECOVERY AT AN AMBIENT TEMPERATURE OF 30°F; AVERAGE LOAD CONDITIONS

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Basis: 100 units of Source Energy Input

Overall Cooling COP, Source Basis 18.01 (Theory)
0.84 (Practice)

Overall Cooling COP, Input to Boiler Basis 18.95 (Theory)
0.83 (Practice)

Figure 3.8. FIRST-LAW ANALYSIS — EHP CENTRAL PLANT — COOLING MODE AT AN AMBIENT TEMPERATURE OF 90°F; AVERAGE LOAD CONDITIONS

combined with the electric driver efficiency of 91% for an overall shaft power efficiency of 27%, compared with the efficiency of the boiler, turbine, and gearbox of only 21.5%. Of course, the first-law comparison does not show the benefit of the HAHP-ICES central plant supplying a substantial amount of thermal energy (52.74 units) at temperatures useful for domestic hot-water and other thermal loads.

Base-case HAHP-ICES cooling COP is not effected by chilled water distribution losses because losses are all assumed to occur in the office building where the central plant is located. However, losses from the thermal distribution system, which primarily supplies domestic hot water to residential loads in the cooling season, result in reduced thermal services in the form of hot water or space heating. A 15% loss from the distribution system results, for example, in a corresponding 15% drop in the amount of thermal energy available per 100 units of source energy to supply space heating or domestic hot water. In the site-specific case, a loss of 15% of the distributed thermal energy in the form of chilled water would reduce the source based cooling COP from 0.84 to 0.68.

3.6.2 Second-Law Analysis

The first-law analysis does not indicate the most efficient manner in which to utilize the energy input to the system. The concept of thermodynamic availability as embodied in the second-law analysis provides a means to technically evaluate processes as to their comparative efficiency in the utilization of energy. The most meaningful comparison on an overall basis is to compare the total maximum work (MW) obtainable in practice from each system. The MW is the product of the thermodynamic availability of the thermal energy appearing at the terminal component of the system (e.g., heat pump condenser or thermal distribution system) and the quantity of energy flowing through the system that finally appears at the terminal component. A comparison may also be drawn between the theoretical (e.g., ideal) performance of a system component operated reversibly and without frictional losses to the performance of the component in practice. This comparison shows the potential for component improvement.

3.6.2.1 Annual Performance — Base Case

Annual second-law performance of the base-case conventional system is presented in Figure 3.9; annual second-law performance of the base-case HAHP-ICES is presented in Figure 3.10. In both cases, the basis is 100 units of primary energy input (assumed to have an availability of 1.0); primary energy required to provide for parasitic loads, such as cooling tower fans and pumps, are included in the primary input to the systems. HAHP-ICES distribution system heat losses are not explicitly considered. Even if the potential work associated with heat rejected at the cooling tower by either system is ignored, HAHP-ICES utilizes primary energy more effectively in that it has greater potential to do work (14 units) than the conventional system (9 units). To gauge the impact of thermal losses from the distribution system on the base-case HAHP-ICES second-law performance, a 15% thermal loss met by gas at an 83% first-law efficiency results in a reduction of potential work by HAHP-ICES from 14 units to 12 units; still very competitive with the potential of only 9 units from the conventional system.

Basis: 100 units of source energy input.

Net Maximum Work I = 13.60 (including availability of rejected heat)

Net Maximum Work II = 9.19 (not including availability of rejected heat)

1. $A = \text{availability}; A = \left[1 - \frac{T_{\text{sink}}}{T_{\text{source}}} \right]$
2. Availability of source energy assumed to be 1.0.
3. $MW = \text{maximum work from process operating between } T_{\text{source}} \text{ and } T_{\text{sink}}. MW = (E)(A).$
4. Heat supplied at 190°F ($= T_{\text{source}}$); T_{sink} is ambient temperature assumed to be 30°C .
5. Domestic hot water supplied at 140°F ; T_{sink} is water supply temperature assumed to be 60°F .
6. $A = \left[\text{COP}_{\text{cool}} \right]^{-1}$. Estimated average seasonal $\text{COP} = 3.81$. Assumes average conditions of 80°F ambient, 80% of full load cooling output, 91% efficient motor and full and part load chiller performance comparable with steam turbine driven chiller.

Figure 3.9. NORMALIZED ANNUAL SECOND-LAW ANALYSIS - BASE-CASE CONVENTIONAL SYSTEM

Basis: 100 units of source energy input

Net Maximum Work I = 20.40 (including availability of rejected heat)

Net Maximum Work II = 13.80 (not including availability of rejected heat)

1. $A = \text{availability}; A = \left[1 - \frac{T_{\text{sink}}}{T_{\text{source}}} \right]$.
2. Availability of source energy assumed to be 1.0.
3. MW = maximum work available from process operating between T_{source} and T_{sink} . $MW = (E)(A)$.
4. Heat supplied at 190°F ($= T_{\text{source}}$); T_{sink} is ambient temperature assumed to be 30°F.
5. Domestic hot water supplied at 140°F; T_{sink} is water supply temperature assumed to be 60°F.
6. $A = [\text{COP}_{\text{cool}}]^{-1}$. Estimated average seasonal COP = 4.00. Assumes average conditions of 80°F ambient; and 80% of full load cooling output. Assumes 50% of load carried by turbine driven chiller at a seasonal COP of 4.19 and 50% by electric chiller at a COP of 3.81.
7. Assumes turbine condenser temperature of 150°F (T_{source}) and ambient temperature of 80°F (T_{sink}).

Figure 3.10. NORMALIZED ANNUAL SECOND-LAW ANALYSIS — BASE-CASE HAHP-ICES

3.6.2.2 Annual Performance — Site-Specific Case

Annual second-law performance of the site-specific conventional system is presented in Figure 3.11; annual second-law performance of the site-specific HAHP-ICES is presented in Figure 3.12. Ignoring the potential work associated with heat rejected at the cooling tower, HAHP-ICES shows better second-law performance than the conventional system in that it has a greater potential to do work (17 units) than the conventional system (13 units).

3.6.2.3 Heating Mode — Average Load Conditions

Comparing the heat pump and a conventional gas furnace providing thermal energy to a load, Figures 3.13 and 3.14 show that the heat pump is a more efficient means of utilization of the input energy because it has the potential for 19 units of work compared with only 10 units from a conventional gas furnace. These results are equally applicable to HAHP-ICES and conventional base and site-specific configurations. The thermal energy from the turbine condenser of the HAHP-ICES has the potential for another 13 units of work for a total of 33 units of possible work from the HAHP-ICES compared with only 10 units of work possible from the conventional gas furnace. The above figures do not include parasitic loads, nor HAHP-ICES thermal distribution losses.

Figure 3.14 also shows the theoretical second-law potential in the heating mode for HAHP-ICES. The ideal system would pump considerably more heat to the heat pump condenser because of a more efficient turbine, no gearbox or parasitic losses, and a more efficient heat pump operating with no temperature differences across its heat exchangers. A second-law analysis shows that the actual heat pump only has the potential for 19 units of work, while the ideal heat pump produces 54 units of work. The thermal distribution system has better second-law performance in practice because of the large, first-law energy throughput. Overall, the actual HAHP-ICES has the potential for 33 units of work, compared with the theoretical potential of 60 units.

The impact of thermal distribution losses on HAHP-ICES second-law performance was explored using an average thermal loss of 15% as an example. Thermal losses of this magnitude will reduce the maximum work available at the heat pump condenser from 19 units to 16 units and from 13 units to 11 units at the turbine condenser. This implies an overall reduction in potential work for HAHP-ICES from 33 units to 28 units. However, even with a second-law potential of 28 units, HAHP-ICES is very competitive with the potential of only 10 units of work from a conventional furnace.

Thus, in the heating mode, the HAHP-ICES outperforms a conventional furnace from the standpoint of both first- and second-law analyses. The second-law does point to areas for improvement in component performance; primarily, in the turbine and heat pump compressors and their associated heat exchangers.

Net Maximum Work I = 16.28
(Including Availability of
Rejected Heat)

Net Maximum Work II = 12.49
(Not Including Availability
of Rejected Heat)

Heat Supplied to
Conditioned Space⁴

E = 44.03

A = 0.25

MW = 11.01

Heat Removed From
Conditioned Space

E = 14.99

A = 0

DHW Supplied⁵

E = 11.36

A = 0.13

MW = 1.48

Primary
Gas
E = 78.11
A = 1.0
MW = 78.11

Primary
Electricity
E = 21.89
A = 1.0
MW = 21.89

Site-Specific
Conventional System

Low-Temperature Heat Rejected
During Cooling Season to Cooling
Tower From Electric Chiller
Condenser

E = 14.59

A⁶ = 0.26

MW = 3.75

Boiler Flue Loss

E = 7.58 DHW

E = 21.81 Space Heat

E_{total} = 29.39

A = 0

MW = 0

Total
Primary
Energy:

100 Units

A^{1,2} = 1.0

MW³ = 100.0

Figure 3.11. NORMALIZED ANNUAL SECOND-LAW ANALYSIS — SITE-SPECIFIC CONVENTIONAL SYSTEM

Figure 3.12. NORMALIZED ANNUAL SECOND-LAW ANALYSIS — SITE-SPECIFIC HAHP-ICES
(Basis: 100 Units of Source Energy Input)
(Four Heat Pump Units)

Basis: 100 Units of Source Energy Input; Ambient Temperature = 30°F

Net Maximum Work = 10.32

1. E = Energy units flowing through system.

2. Adiabatic flame temperature assumed to be 2700°F.

3. A = Availability $A = 1 - \frac{T_{\text{sink}}}{T_{\text{source}}}$

$T_{\text{sink}} = 30^\circ\text{F}$; $T_{\text{source}} = \text{sendout temperature}$.

4. MW = Maximum work from process operating between T_{source} and T_{sink} .
MW = (E)(A).

Figure 3.13. SECOND-LAW ANALYSIS - CONVENTIONAL GAS-FIRED FURNACE; AVERAGE LOAD CONDITIONS

Basis: 100 Units of Source Energy Input

Net Maximum Work (Theory) = 59.93

Net Maximum Work (Practice) = 32.54

Figure 3.14. SECOND-LAW ANALYSIS — HAHF CENTRAL PLANT — HEATING MODE WITH INTERNAL HEAT RECOVERY AT AN AMBIENT TEMPERATURE OF 30°F; AVERAGE LOAD CONDITIONS

3.6.2.4 Cooling Mode — Average Load Conditions

Figures 3.15 and 3.16 compare the performance of a conventional electric chiller to a practical HAHP-ICES in the cooling mode. The second-law analysis does not include parasitic loads, nor thermal distribution losses. Comparing the conventional electric chiller to the heat pump, it is found that a conventional chiller is capable of producing more work at its condenser, 38 units, than the 25 units of work possible from the heat pump. Even including the benefits of turbine condenser heat in producing additional potential work, 4 units, the total of 30 units of possible work from the HAHP-ICES is less than the potential work from the conventional electric chiller of 38 units.

In the base case, thermal distribution losses apply only to energy flows at the steam turbine condenser. There are no losses from the chilled water distribution system because all losses are to the conditioned space — the office building — because the central plant is assumed to be located in the equipment room of the office building. As an example of the impact of losses from the thermal distribution system on second-law cooling mode performance, a 15% loss of thermal energy produced at the steam turbine condenser reduces the maximum potential work from HAHP-ICES in the cooling mode from 30 to 29 units, which further increases the gap in second-law performance between HAHP-ICES and the conventional chiller with a potential for 38 units of work.

In the site-specific case, additional losses occur from the chilled water distribution system. For the purposes of the second-law analysis, a loss of 15% of the thermal energy removed from the conditioned space may be considered as a reduction in useful work available at the heat pump condenser. In this case, the heat removed from the conditioned space would be reduced 15% from 84 units to 71 units, resulting in a reduction in energy at the heat pump condenser from 104 units to 92 units, with a corresponding reduction in potential work of 3 units. Adding the impact of losses from the hot water distribution loop of 1 unit to this, the available work from the site-specific HAHP-ICES is only 26 units compared with the conventional chiller with a potential for 38 units of work.

The second-law analysis points toward the deficiency in the HAHP-ICES. This deficiency is the lower availability of energy from the generation of mechanical energy in the turbine and gearbox than the availability of energy from a central electric generating plant. That is, the central electric generating plant produces more available work than the HAHP-ICES steam turbine and gearbox and, thus, ultimately results in a greater amount of potential work at the condenser of the conventional chiller.

The potential for improvement to the heat pump system as compared with an ideal system is also shown in Figure 3.16. The ideal system would pump considerably more heat out of the conditioned space because of a more efficient turbine, no gearbox or parasitic losses, and a more efficient heat pump. A second-law analysis shows that the actual heat pump has the potential for only 25 units of work compared with 52 units for the ideal machine. However, the thermal distribution system has better second-law performance in practice because of the large, first-law energy throughput. Overall, the actual HAHP-ICES has the potential for 30 units of work compared with the theoretical potential of 54 units.

Basis: 100 units of source energy input

Net Maximum Work (Theory): 85.33

Net Maximum Work (Practice): 37.62

1. E = Energy units flowing through system.

2. A = Availability.

$$A = \left[1 - \frac{T_{\text{sink}}}{T_{\text{source}}} \right]$$

$T_{\text{sink}} = 90^{\circ}\text{F.}$

3. MW = Maximum work from process operating between T_{source} and T_{sink} . $MW = (E)(A)$.

4. Actual cycle efficiency assumed to be 32%. Transmission loss assumed to be 7.25%.

5. $\text{COP (Theory)} = \left[\frac{T_{\text{ambient}}}{T_{\text{room}}} - 1 \right]^{-1}$

6. $A = (\text{COP})^{-1} \left[\frac{T_{\text{ambient}}}{T_{\text{room}}} - 1 \right]$; $T_{\text{room}} = 75^{\circ}\text{F.}$

Figure 3.15. SECOND-LAW ANALYSIS - CONVENTIONAL ELECTRIC CHILLER - COOLING MODE AT AN AMBIENT TEMPERATURE OF 90°F; AVERAGE LOAD CONDITIONS

Figure 3.16. SECOND-LAW ANALYSIS — HAHF CENTRAL PLANT — COOLING MODE AT AN AMBIENT TEMPERATURE OF 90°F; AVERAGE LOAD CONDITIONS

The conventional chiller also shows much room for improvement. As depicted in Figure 3.15, a theoretical power generation cycle and an ideal electric chiller could produce 85 units of work, compared with a potential of only 38 units of work from an actual electric chiller. The theoretical performance of the electric chiller exceeds that of the heat pump 85 to 54 units.

The results of the first- and second-law analyses of the HAHP-ICES and conventional equipment points out some advantages and disadvantages of the heat pump system from a technical standpoint. On an annual basis, HAHP-ICES outperforms conventional heating and cooling systems on a first- and second-law basis. In the heating mode, the HAHP-ICES looks superior to a conventional furnace both in terms of energy throughput and good utilization of input energy. However, in the cooling mode, the conventional electric chiller shows a greater overall COP and a more effective utilization of input energy than the heat pump, primarily due to better use of primary input energy for the production of power to drive the compressor. The second-law analysis also illustrates a significant potential for improvement of component performance.

3.7 Use of Absorption Chiller — Site-Specific Case

A second-law analysis would suggest that a thermodynamic advantage would accrue to HAHP-ICES if heat pump turbine condenser heat in excess of that used to satisfy domestic hot water loads is used to drive an absorption chiller rather than being rejected at the cooling tower. Several simulations of HAHP-ICES performance with and without an absorption chiller were made to investigate the potential of this alternative configuration. The results, based on a HAHP-ICES with three turbines, indicated that the system without an absorption chiller was economically better than a system with an absorption chiller. An analysis of the reason for this result may start by examining Table 3.19.

Table 3.19. EVALUATION OF POTENTIAL ABSORPTION CHILLER
FUEL LOAD OPERATING HOURS

<u>Number of Heat Pump Units</u>	<u>High-Temperature Turbine Condenser Heat Available After Domestic Hot Water Loads Are Satisfied (Btu)</u>	<u>Full Load Hours of 100-ton Absorption Chiller @ COP = 0.7 (Hours)</u>
0	0	0
1	0	0
2	13.4×10^6	7.8
3	40.98×10^6	23.9
4	183.3×10^6	107.8

Table 3.19 depicts the waste heat rejected at the cooling tower of HAHP-ICES after domestic hot water loads are satisfied with zero through four heat pump units, with a condenser temperature of 140°F. A condenser temperature of 200°F would be necessary to drive an absorption chiller so the results presented

are conservative because the higher condenser temperature reduces turbine efficiency and produces more waste heat. It may be seen that even with four heat pump units, only about 100 full-load cooling hours are possible using a 100-ton chiller. (Each heat pump unit has sufficient exhaust heat for approximately 50 tons of absorption chiller capacity.) Thus, the first reason for the poor performance of an absorption chiller in HAHP-ICES is that there is insufficient waste heat after domestic hot water loads are satisfied to get sufficient economic utilization of an absorption chiller directly fired from turbine exhaust. As a result, in order to utilize the absorption chiller capacity to satisfy the cooling loads of the community, the absorption chiller must go directly to the boiler for heat. This might be a promising proposition, because at current energy costs, a Btu of cooling from the absorption chiller is cheaper than a Btu of cooling from an electric chiller. The reason this does not make the use of an absorption chiller an economic proposition can only be understood at the system level; with the introduction of an absorption chiller, the overall cost per ton of cooling machinery increases (\$516/ton with absorption chiller versus \$483/ton without absorption chiller, overall) because the sizes of individual pieces of cooling machinery are reduced and cooling machinery costs are, of course, sensitive to scale. Thus, the cost differential is about \$26,000 more for a system using absorption chillers over an overall system cost with three heat pump units and no absorption chiller of \$860,000. However, the effect of an absorption chiller is to reduce the energy operating costs of the system by only \$800 per year. As a result, the absorption chiller, while increasing the second-law thermodynamic performance of the system, cannot pass the economic test of paying back increased capital costs in terms of energy savings in a short enough time to warrant its use in the HAHP-ICES design.

3.8 Summary and Conclusions

In this section, we will summarize the major findings and conclusions determined in the evaluation of the performance of the HAHP-ICES concept as compared with the conventional HVAC equipment.

3.8.1 HAHP-ICES Annual Performance — Base Case Findings

- In its base-case configuration, the HAHP-ICES saves significant amounts of primary energy compared with conventional systems. Of the four cities evaluated, primary energy savings range from 33% in Chicago down to 18% in Atlanta. Primary energy savings are reduced somewhat by distribution system thermal losses.
- The HAHP-ICES favors a load mix that requires a minimum of additional supplemental heat supplied by conventional equipment.
- The HAHP-ICES favors geographic locations that provide a heating load of sufficient duration to maximize the benefits of the HAHP-ICES energy efficiency potential in the heat pumping mode.
- The HAHP-ICES favors a load mix which allows simultaneous heating and cooling in both summer and winter.

3.8.2 HAHP-ICES Annual Performance — Site-Specific Case Findings

- The HAHP-ICES, in its site-specific configuration, saves significant amounts of primary energy. For Pittsburgh, Pennsylvania climate conditions, primary energy savings including distribution system thermal losses, range from 15.4% for HAHP-ICES with one heat pump unit, up to 21.5% with four heat pump units.

3.9 Reference Cited

1. Urban, R.A., Byers, Urban, Klug and White, private communication, March 1979.

4. ECONOMICS

The purpose of this section is to report on the economic feasibility of the HAHP-ICES with respect to the individual community members of the system. The base-case application of the HAHP-ICES concept consists of office and residential components: a single, six-story office building; and five, two-story 24-unit, low-rise apartment buildings. The HAHP-ICES central plant functions as the thermal utility, supplying heating and domestic hot water to the entire community and cooling to the office building. Base-case thermal loads for heating and cooling were established using Chicago weather data, with energy costing based upon Cleveland rates. In the context of this report, economic feasibility entails the meeting of the return requirements of the HAHP-ICES thermal utility, which owns and operates the HAHP-ICES central plant, while at the same time ensuring that the building owners at lease maintain the same level of profitability on their overall investment as if they had opted for a conventional heating and cooling system. The determinate of economic feasibility will be the result of our financial model which is interchangeably referenced as PV_{ds} , or the system surplus. This amount will be used to defray the life-cycle cost of the thermal distribution system for any site-specific application of the HAHP-ICES.

In Section 4.1, we will discuss the methodology and derivation of the economic model employed in the analysis. Section 4.2 discusses the unapplicability of the traditional cost of service approach to the economic analysis of the HAHP-ICES. Section 4.3 details the economics of the base case. Section 4.4 consists of the sensitivity analyses, with separate subsections on: 1) the impact of selected variables on the base-case results, 2) the impact of geographic locations, 3) the impact of various energy rate schedules on the economic feasibility of the HAHP-ICES, and 4) the impact of thermal losses from the distribution system on the base-case results. Section 4.5 presents the site-specific application of the HAHP-ICES concept; and Section 4.6 offers conclusions in the form of a summary of items which have been identified as being favorable to the economics of the HAHP-ICES. Table 4.1 presents the definitions of the terms used in this section.

4.1 Methodology^{*}

The objective of the economic model is to determine whether the owners of the HAHP-ICES central plant can earn a pre-tax rate of return that meets or exceeds their minimum return requirements for investment. Because the HAHP-ICES central plant is supplying heating and air conditioning to the community of residential and office buildings, it can be thought of as a "thermal utility;" thus, these terms will be used interchangeably throughout the text.

^{*} See Section 9.5 for presentation of the mathematics used in the economic analysis.

Table 4.1. DEFINITIONS OF TERMS USED IN THE METHODOLOGY

Amortization:	Liquidation, as in debt, over a period of time; an amortized loan is one in which the principal portion of the loan has been repaid over the life of the loan.
Annualized:	Converted from a single amount, or a series of unequal amounts, into a series of equal amounts over a specified period of time.
Annuity:	A stream of uniform periodic amounts over a given time period.
Discount Rate:	The effective interest rate used in the discounting process, reflecting that the value of a cash flow is dependent upon the time at which it occurs.
Discounting:	The process of finding the value at a specific time of one or more cash flows occurring in the future. Discounting can be thought of as the reverse of compounding.
Escalation:	Refers to a change in the price of a good or service with time. These changes are caused by fluctuations in the purchasing power of money or actual changes in the price of a good or service resulting from any number of economic forces, e.g., supply and demand variations.
Internal Rate-of-Return:	The rate-of-return on an asset investment. The internal rate-of-return is calculated by finding the discount rate that equates the present value of an equity investment to the present value of the resulting future cash flows.
Present Value:	The value of a payment, or stream of payments, discounted at an appropriate rate to reflect the time value of money. The present value of a cash flow can be thought of as its real value adjusted for any interest that may be earned or paid between the time of the actual flow and a specified "present" time. The appropriate discount rate can be the firm's cost of capital or various subjective return requirements selected for the analysis.
PV _(subscript) :	The present value of the cash flow represented by the subscripted symbol.
PV()::	Present value operator. The present value of the cash flow inside the parentheses.
PV _{hr} :	The present value of the heating and cooling charges that must be paid by the residential owners to the utility. The annualized value of these charges is a component of the utility's revenue.
PV _{ho} :	The present value of the heating and cooling charges that must be paid by the office building owner to the utility. The annualized value of these charges is a component of the utility's revenues.
PV _{ds} :	The total present value of the utility's pre-tax cash flows. It is available to construct the thermal distribution system.
T, t, Tax Rate:	The income tax rate that the firm must apply to its pre-tax profits (taxable income) to determine its annual tax liability. As used in the methodology, it is adjusted to reflect any tax preference items, (the investment tax credit, state and local taxes, etc.).

The return calculations are based on a present value analysis of the various incoming and outgoing cash flows. The discount factors used are equal to the rates-of-return required by each component - residential, office, and the HAHP-ICES thermal utility. In the case of the residential and office components, the net present value of the cash flows for each of the components is annualized and credited by the HAHP-ICES thermal utility as a payment for the thermal energy supplied throughout the year. The thermal energy consists of heating for the residential and office buildings and air conditioning for the latter. In the HAHP-ICES thermal utility's case, the resulting net present value reflects the degree to which system-resultant revenues exceed system-resultant costs (exclusive of the life-cycle cost of the thermal distribution system). The discount rate employed in the present value analysis reflects the rate of return required by the HAHP-ICES thermal utility on invested capital. The system surplus would be used to defray the life-cycle cost of the thermal distribution system.* A life-cycle cost refers to the present value, as of the first year of commercial operation, of all costs associated with a given component that are incurred throughout the lifetime of the project. These costs typically include the installed cost, annual operating and maintenance expenses, and other financial considerations. However, the lifetime expenses beyond the initial installed cost of the distribution system are assumed negligible, and thus, for the purposes of the initial analysis, the life-cycle cost of the distribution system is equivalent to its installed cost. The maintenance of the distribution system circulating pumps is included in the central plant's annual operating and maintenance expenses; any additional maintenance expenses for the distribution network could only be associated with an extraordinary occurrence (e.g., accidental breakage).

The data requirements of the model are an economic description of the HAHP-ICES as it relates to its individual components (i.e., residential, office, and thermal utility). This description includes an anticipated date of commercial operation (1990), an expected operating life (20 years), and cash flows associated with the capital and operating costs of the system. These costs include interest, depreciation, energy requirement costs, operating and maintenance expenses, insurance, and property taxes. Capital investment cash flows consist of cash outlays to purchase and install all necessary equipment, with the exception of the thermal distribution system. Operating and maintenance costs remain constant over the first half of the project's life and are then incremented and held level over the second half. In the intermediate calculations, depreciation, interest, and amortization* of the principal vary yearly, depending upon the depreciation and financing method employed.

The methodology employed to analyze the viability of the HAHP-ICES for the residential and office components of the community involved deriving a break-even annual "thermal charge." That is, given all the costs associated with purchasing, installing, and operating the HAHP-ICES, what price would these sectors be able to pay for their heating and air-conditioning requirements so that the overall rate-of-return on their property investment will be essentially the same as with a conventional heating/cooling system?

* The exact configuration of the building community (and thus, the resulting cost of the thermal distribution system) will vary for each HAHP-ICES application. Therefore, the excess that is available to construct the thermal distribution system will become the measure of economic feasibility for any site-specific application.

In general, the model uses accepted capital budgeting techniques. These techniques compare expected revenue and expense cash flows that have been corrected for the influence of the timing of the flows relative to the project's life. All costs are expressed in current (1979) dollars. Escalation adjustments are used only for energy costs in the sensitivity analysis, when they are expected to rise faster than general inflation.

The model used to evaluate the acceptability of the HAHP-ICES to the thermal utility uses essentially the same methodology as in the case of the residential and office elements. However, there exists the following exceptions:

- a. The HAHP-ICES thermal utility's revenues are equal to the present value of the acceptable annualized energy costs for the group of residential and office buildings.
- b. The cost of the energy consumed to produce the heating and air conditioning is treated as an actual cost.
- c. Operating and maintenance expenditures are treated as actual costs to the utility, not differential (with respect to a conventional system) costs.
- d. The calculations are on a pre-tax basis.
- e. The model determines the excess of the present value of the revenues over the present value of the costs.

This represents the amount that is not needed to provide the required return on the HAHP-ICES thermal utility's equity investment and thus, is available for the construction of the thermal distribution system.

4.2 Cost of Service for the HAHP-ICES

Before any conclusions can be drawn as a result of the interpretation of the economic studies, certain points warrant further clarification and re-emphasis.

In general, comparative evaluations of energy technologies attempt to provide a unitized energy cost—be it in mills per kilowatt hour, or—as this case would necessitate, dollars per million Btu of energy to facilitate some measure of quick comparison between the alternative systems. However, in the case of the HAHP-ICES, any such "common denominator" approach would at best be misleading and at worst be invalid. The invalidity of the conventional unit cost of energy approach stems from the nature of the product/service being offered by the HAHP-ICES thermal utility as well as the interdependent relationship that is inherent to any ICES.

The HAHP-ICES thermal utility provides a "finished product" rather than an intermediate product, to the residential and office members of the community. In this sense, a finished product is interpreted to mean that the thermal energy, such as that supplied by the HAHP-ICES thermal utility, is in a form suitable for direct utilization to satisfy thermal energy requirements; whereas an intermediate product (such as natural gas, electricity, etc.) is subject to further processing (by a furnace or chiller) before a suitable thermal output

is obtained. Hence, the two products are not comparable because of the lack of a common basis for a unitized cost of energy analysis. Furthermore, any attempt to provide a common basis for comparison, such as energy supplied to the HAHP terminal units, is obfuscated by the simultaneous production of heating and cooling that is inherent to the HAHP-ICES concept.

The lack of a common comparative basis for a unitized cost of energy analysis and the interdependency of the community members necessitates the derivation of a component-specific and thus, a community-specific, annual cost of service. The cost of service for the HAHP-ICES thermal utility is a function of many variables, namely the community configuration and composition, the heating and cooling loads of the individual community members, the reduction in the initial investment and operating and maintenance expenses resulting from the implementation of the HAHP-ICES (as opposed to a conventional system) for individual community members, energy rates schedules, climatic conditions specific to a given geographic location, as well as other site- and member-specific criteria. Thus, the only valid comparison of the relative economic merits of the HAHP-ICES and a conventional HVAC system is one made on the basis of their respective annual cost of services to community members at a given site.

Throughout this analysis, the approach to the evaluation of the annual cost of service has been to set the cost of service for both the HAHP-ICES and conventional systems to the community members equal to each other (at the conventional system cost level) and use the allowed cost of a distribution system for the HAHP-ICES as a measure of its viability.

Although we do not develop a unit cost of service, it is recognized that in the real world some mechanism must exist for customer rate adjustments based on annual weather variations during the commercial operation of the HAHP-ICES. Along with that mechanism must come a cost, and that cost must be accounted for in the economic analysis. To that end, we have assumed block metering for the HAHP-ICES community members and the cost of the metering has been provided for in the distribution system's cost.

4.3 Base Case

The economic evaluation of the HAHP-ICES was based on the treatment of each component as an independent entity, that is, the apartment building complex (consisting of five buildings), the office building, and the HAHP-ICES thermal utility are treated as separately-financed, independent operations. The residential and office components were required to have a net break-even situation on energy costs, provided that any acceptable project would have an after-tax internal rate-of-return of 8%. The residential and office buildings experience a reduction in capital expenditure with the HAHP-ICES when compared with a conventional system. The residential and office buildings were assumed to be financed through mortgages under the following conditions:

	<u>Residential</u>	<u>Office</u>
Life (no salvage), years	20	20
Mortgage, %	80	75
Interest, %*	8	10
Depreciation	DDB w/switch **	DDB w/switch **
Depreciation Bonus	yes	yes
Insurance, % of investment	1	1
Property Tax, %	1	1
Tax Rate, %	50	50

The HAHP-ICES thermal utility was assumed to have revenues equivalent to the annualized energy costs that the office and residential buildings could support for a break-even situation. The utility was assumed to require an internal rate-of-return of 15% before taxes. This value coincides with the current experience of the five most profitable large utilities in the United States. If the HAHP-ICES is to be an attractive venture, one would hope that it could yield as high a rate-of-return as that which the most profitable utilities currently realize from conventional operations. The financing of the HAHP-ICES thermal utility was assumed to be standard utility with equal load amortization payments each year. The following chart describes the basic assumptions:

	<u>HAHP-ICES Thermal Utility</u>
Life (no salvage), years	20
Loan, %	75
Interest, %	10
Depreciation	DDB w/switch **
Depreciation Bonus	no
Insurance, %	1
Property Tax, %	1

The allowable annualized energy costs were determined using after-tax current value calculations with an 8% discount rate. The determination of the economic condition of the HAHP-ICES thermal utility was made by calculating the current value of the pre-tax excess revenues over the various cash and non-cash costs and equity investment, using a 15% discount rate. The non-cash expenses (depreciation) and non-expense items (amortization of debt and equity investment) were adjusted back to a pre-tax basis. The analysis shows that the current value of the pre-tax excess is \$31,586. This excess represents the total capital cost which would be allowed for the thermal distribution system. If the excess surpasses the cost of the distribution system, the resulting surplus can be returned to the residential and office components in the form of a reduction in annual energy costs, or accrue to the owner of the HAHP-ICES thermal utility as a higher rate-of-return.

* The values, such as the chosen interest rate, are used to determine the annual cost of service for a conventional HVAC system on a differential basis with the HAHP-ICES. Overstating the economic potential of a HAHP-ICES application is avoided by conservatism in these estimates.

** Double declining balance with switch to straight line in Year 11.

For the office and residential configuration presented as Figure 1.2 in Section 1, a distribution system cost of about \$45,000 has been estimated. A detailed presentation of the distribution system is contained in Section 9.6.

Costs assumed on the above analysis are shown in Table 4.2, with the basis upon which these costs were developed presented in Section 9.4.

Table 4.2. COSTS ASSUMED IN BASE CASE ECONOMIC ANALYSIS

Residential Component (Five Buildings):

Building Cost	\$80,150 decrease
O & M Per Year	\$6,200 decrease
Energy Cost With Conventional System	\$21,540/year*

Office Building:

Building Cost	\$99,397 decrease
O & M (first 10 years) ^{2,3} Per Year	\$3,500 decrease
(next 10 years) Per Year	\$7,000 decrease
Energy Cost With Conventional System	\$9,516/year*

HAHP-ICES Thermal Utility:

Installed Cost	\$172,444
O & M (first 10 years) ^{2,3}	\$8,250/year
(next 10 years)	\$12,000/year
Energy Costs	\$23,416/year

* Displaced with heat-pump-based system.

4.4 Sensitivity Analyses on the Base Case

In order to evaluate the effect of various internal and external factors in the economic feasibility of the HAHP-ICES, five separate sensitivity analyses were performed. The results are presented in Subsections 4.4.1, 4.4.2, 4.4.3, 4.4.4, and 4.4.5. A summary is presented in Subsection 4.4.6.

4.4.1 The Impact of Selected Economic Variables on the Base Case Results

Eleven independent variables were chosen to undergo sensitivity analysis in order to evaluate their individual effects on the economic viability of the model at hand. These are:

• Discount Rate: (Residential and Office)	Variations which reflect the profit-ability requirements for the residential and office components.
• Interest Rate: (Office and Utility)	Variations in the cost of debt to these sectors.
• Interest Rate: (Residential)	Variations in the cost of debt to the residential owners.
• Capital: (All Sectors)	Changes in the capital funds required to implement the system for all the components.
• Capital: (Residential)	Variations in the capital funds required by the residential owner to implement the system.
• Capital: (Office)	Variations in the capital funds required by the office building owner to implement the system.
• Capital: (HAHP-ICES Thermal Utility)	Variations in the cost of the HAHP-ICES central plant.
• Operating and Maintenance:	Changes in the labor and materials cost required for the operation of the HAHP-ICES.
• Cost of Energy: (Relative to Inflation)	Reflects the annual rate at which the price of energy increases relative to general inflation.
• Cost of Energy: (Gas versus Electricity)	Reflects the annual rate at which the price of gas and electricity change relative to each other.

The size and range of the variations from the base-line assumptions were chosen by the Project Team and are considered reasonable and representative considering the technical, market, and resource environments predicted for the time frame of the study. These variations are shown in Table 4.3.

Table 4.4 presents the results of the sensitivity analyses. The impact of thermal losses from the distribution system were not included in these analyses. The following is a discussion of the results by variable.

Table 4.3. SELECTED VARIABLES USED IN THE SENSITIVITY ANALYSES

	<u>Base Case</u>	<u>High Extreme</u>	<u>High Midrange</u>	<u>Low Midrange</u>	<u>Low Extreme</u>	<u>Base Case</u>
Discount Rate (Residential and Office)	8%	15%	10%	6%	4%	8%
Interest Rate (Office and MAHP-ICES Thermal Utility)	10%	15%	12%	8%	6%	10%
Interest Rate (Residential)	8%	12%	10%	6%	4%	8%
Capital (All Sectors)	100%	130%	115%	85%	70%	100%
Capital (Residential)	100%	130%	115%	85%	70%	100%
Capital (Office)	100%	130%	115%	85%	70%	100%
Capital (MAHP-ICES Thermal Utility)	100%	130%	115%	85%	70%	100%
Operating and Maintenance	100%	150%	125%	75%	50%	100%
Cost of Energy (Relative to Inflation)	--	+6% annual	+4% annual	+2% annual	-2% annual	--
Cost of Energy (Gas vs Electricity)	--	+6% annual electricity	+4% annual electricity	+2% annual gas	+6% annual gas	--

Table 4.4. THE IMPACT OF SELECTED VARIABLES ON THE BASE CASE RESULTS

	Base Case	High Extreme	High Midrange	Low Midrange	Low Extreme
Discount Rate (Residential and Office)	8% 31,586 *	15% 42,830* +35.6%	10% 33,927* +7.4%	6% 29,997* -5%	4% 29,173 * -7.6% **
Interest Rate (Office and HAHF-ICES Thermal Utility)	10%	15% 19,995* -36.8%	12% 26,642* -15.7%	8% 36,988* +17.1%	6% 42,908 * +35.8% **
Interest Rate (Residential)	8%	12% 43,068* +36.4%	10% 37,130* +17.6%	6% 26,487* -16.1%	4% 21,883 * -30.7% **
Capital (All Sectors)	100%	130% -59,588* -288.7%	115% -14,001* -144.3%	85% 77,172* +144.3%	70% 122,759 * +288.7% **
Capital (Residential)	100%	130% 14,020* -55.6%	115% 22,803* -27.8%	85% 40,369* +27.8%	70% 49,151 * +55.6% **
Capital (Office)	100%	130% 7,302* -76.9%	115% 19,444* -38.4%	85% 43,727* +38.4%	70% 59,869 * +76.9% **
Capital (HAHF-ICES Thermal Utility)	100%	130% -17,738* -156.1%	115% 6,924* -78%	85% 56,248* +78%	70% 80,910 * +156.1% **
Operating and Maintenance	100%	150% -30,386* -196.2%	125% 600* -98.1%	75% 62,571* +98.1%	50% 93,557* +196.2% **
Cost of Energy (Relative to Inflation)		+6% annual 89,334* +182.8%	+4% annual 64,799* +105.1%	+2% annual 46,000* +45.6%	-2% annual 20,521* -35% **
Cost of Energy (Gas vs Electricity)		+6% annual elec. 56,511* +78.9%	+3% annual elec. 41,792* +32.3%	+3% annual gas 44,569* +41.1%	+6% annual gas 64,408* +103.9% **

* Middle value is PV_{1g} . PV_{dg} = the total present value of the utility's pre-tax cash flows. It is available to construct the thermal distribution system.

** Percent change in PV_{dg} from base case.

Discount Rate (Residential and Office): During this aspect of the analysis (see Row 1), the discount rate for the residential and office components was varied from 15% to 4% (base case being 8%). All other variables in the base-case were held constant. In this sense, the discount rate can be thought of as both the percentage rate-of-return requirement and the reinvestment rate. The reinvestment rate is defined as the rate-of-return at which cash flows from a project are reinvested. As can be seen in Table 4.11, Row 1 (PV_{ds}), the present value of the pre-tax excess available for the construction of the thermal distribution system varies directly with the discount rate. A discount rate of 15% results in approximately a 35.6% increase in PV_{ds} (relative to the base case), while at a discount rate of 4%, there is an approximate 2.6% reduction of PV_{ds} (relative to the base case). This is due to the fact that the higher rate-of-return at which the annual benefits (capital and cost reductions) derived from the implementation of the HAHP-ICES are assumed to be reinvested, yields a greater annual thermal energy charge that the residential and office components could support for a break-even situation. The resulting increase in the revenues of the HAHP-ICES thermal utility is reflected in the value of PV_{ds} .

Interest Rate (Office and Utility): In this analysis, the interest rate for the office and HAHP-ICES thermal utility was varied from 15% to 6% (base case being 10%). All other variables with respect to the base case were held constant. Since the office building experiences a reduction in investment with the HAHP-ICES, the effective annual savings will vary directly with the interest rate. However, the HAHP-ICES thermal utility is facing a greater cost of debt on its disproportionately larger capital requirements. Thus, PV_{ds} moves inversely with the interest rate applicable to the office and HAHP-ICES thermal utility.

Interest Rate (Residential): In this analysis, the residential interest rate was varied from 12% to 4%, holding all other variables constant with respect to the base case. As with the office component in the previous analysis, the greater the interest rate the greater the effective savings will be to the residential owners. This increase in the effective savings yields a higher annual thermal energy charge that the residential owners could support for a break-even situation. Since the HAHP-ICES thermal utility's costs have not risen, the resultant increase in revenues is reflected in an increase to PV_{ds} . A 12% residential interest rate results in approximately a 36.4% increase in PV_{ds} from the base case.

Capital (All Sectors): During this aspect of the analysis, the capital requirements of the HAHP-ICES were varied from 130% to 70% of the base case values for all of the components. An increase in the capital requirements for the HAHP-ICES entails a higher actual investment for the HAHP-ICES thermal utility, and a decrease in effective savings for the residential and office components. A decrease in the system capital requirements (with respect to a conventional system) will result in increased effective savings for the office and residences. The HAHP-ICES thermal utility will require a lower investment. The system is highly sensitive to changes in the capital requirements, especially when these changes occur simultaneously for all three components. A $\pm 30\%$ change in the capital requirements results in approximately a $\pm 288.7\%$ change in PV_{ds} relative to the base case. The effect is typical for a capital-intensive technology.

Capital (Residential): In this analysis, the capital requirements of the residential units were varied from $\pm 30\%$ respective to the base case. All other base case variables were held constant. The increase in effective savings that a reduction in capital entails, results in a higher annual thermal energy charge that can be supported by the residential owners in a break-even situation. The resultant increase in the revenues of the HAHP-ICES thermal utility is reflected in a higher value of PV_{ds} . Thus, a 30% increase in the capital requirements resulted in a 55.6% decrease in PV_{ds} and a 30% capital decrease is reflected in a value of PV_{ds} that is 55.6% higher than the base case value.

Capital (Office): The capital required by the office components for the implementation of the HAHP-ICES was varied from $\pm 30\%$ respective to the base case, while holding all other base case variables constant. The effect on the value of PV_{ds} of varying the office building's capital requirement is the same as with varying the residential requirements. The value of PV_{ds} is inversely proportional to the change in the investment required for the implementation of the HAHP-ICES. A $\pm 30\%$ change in the capital requirements results in a $\pm 76.9\%$ change in the value of PV_{ds} .

Capital (HAHP-ICES Thermal Utility): In this analysis, the capital requirements of the HAHP-ICES thermal utility were varied from $\pm 30\%$ respective to the base case values under a ceteris paribus assumption. The value of PV_{ds} in this case moves directly with the capital investment that is required for the HAHP-ICES thermal utility. A $\pm 30\%$ change in these requirements results in a $\pm 156.1\%$ change in the value of PV_{ds} . Of all the components, the HAHP-ICES thermal utility is the most sensitive to changes in capital requirements.

Operating and Maintenance: The operating and maintenance requirements of the HAHP-ICES were varied $\pm 50\%$ from the base case values. All the other base case variables were held constant. An increase in HAHP-ICES operating and maintenance requirements would result in a decrease in effective savings for the residential and office components and an increase in actual cost for the HAHP-ICES thermal utility. Thus, from the HAHP-ICES thermal utility's point of view, their revenues are decreasing (because the residential and office components must support a lower annual thermal energy charge in order to maintain a break-even situation) at the same time their operating and

maintenance costs are increasing. Thus, the value of PV_{ds} declines as operating and maintenance costs are increased. The reverse is true when operating and maintenance costs are decreasing. Specifically, PV_{ds} increases as the operating and maintenance cost decrease. A $\pm 50\%$ change in these expenses results in an approximate $\pm 196.2\%$ change in the value of PV_{ds} .

Cost of Energy (Relative to Inflation): In this analysis, an annual escalation factor was applied to all energy costs while holding all other base case variables constant. For example, the $+6\%$ rate is interpreted to mean that energy costs are annually rising 6% faster than general inflation over the life of the project. Energy savings for the residential and office components are based on displaced energy usage with respect to a conventional system. The HAHP-ICES thermal utility consumes less energy in providing the necessary heating and cooling needs of the residential and office components, than their respective conventional systems. Hence, as the energy rates in general rise, so do the effective savings of the residential and office components, which are transferred to the HAHP-ICES utility as revenues. This increase in revenues more than offsets the increase in energy costs to the HAHP-ICES thermal utility. Therefore, the value of PV_{ds} varies directly with the escalation factor employed. A $\pm 6\%$ change in these expenses results in an approximate $\pm 182.8\%$ change in the value of PV_{ds} .

Cost of Energy (Gas Versus Electricity): In this column, an annual escalation factor was applied to the cost of one element of energy (i.e., either gas or electricity) while holding the other element and all other base case variables constant. For example, the $+6\%$ escalation factor for electricity is interpreted to mean that electrical costs are rising 6% faster than gas costs on an annual basis. Effective energy savings are based on displaced gas usage for the residences and displaced electricity usage for the office building. Energy consumption by the HAHP-ICES thermal utility is composed of both elements, gas and electricity.

When the cost of electricity is rising faster than the cost of gas, the increase in PV_{ds} relative to the base case is due to the fact that relatively cheaper gas in the more energy efficient HAHP-ICES is displacing the demand for electricity that the office building experienced with a conventional heating and cooling system. This results in an increase in the effective savings for the office which is passed through to the HAHP-ICES thermal utility as an increase in revenues. This more than offsets the increased cost of electricity for the HAHP-ICES thermal utility, and the value of PV_{ds} will rise.

When the cost of gas is rising faster than the cost of electricity, the HAHP-ICES (viewing PV_{ds} as the determinant of economic viability) becomes more favorable. Since the HAHP-ICES has a lower net energy requirement than a conventional system, the increase in effective savings for the residential components results in an increase in the HAHP-ICES thermal utility's revenues that more than offsets the increased cost of gas that the central plant requires in its operation.

4.4.2 Impacts of Geographic Locations

This area of the sensitivity analysis evaluates the impact of various heating and cooling loads intrinsic to different geographic locations on the economic viability of the HAHP-ICES. For the office building, the peak air-conditioning requirement for each selected city was compared with that of the base-case city of Chicago. The cooling load was then varied proportionally. Because the air-conditioning capacity of the HAHP-ICES is fixed in the computer simulation, the size of the office building was varied to accommodate the peak cooling load. The HAHP-ICES thermal utility's capital requirements were varied in two cases, when climatologically imposed load requirements necessitated a change in the auxiliary boiler for the HAHP-ICES central plant. An additional investment of \$7222 was required for Minneapolis while a decrease of \$7444 was appropriate for Atlanta relative to the base case. All other variables were held constant with respect to the base case to provide a meaningful basis for comparison. The four geographic locations selected for this analysis were: Chicago (base-case city, Midwest); Minneapolis (North); Kansas (Midwest); and Atlanta (Southeast). The selected cities and their respective values of PV_{ds} , their geographic locations, their climatic regions, and their seasonal degree-day totals are given in Table 4.5.

The resultant values of PV_{ds} indicate that the HAHP-ICES favors geographic locations that provide a sufficient heating load to maximize the HAHP-ICES' energy efficiency potential (in heat pumping).

4.4.3 Impacts of Various Rate Schedules

This area of the sensitivity analysis examines the effect of various energy-rate schedules on the economic feasibility of the HAHP-ICES (in terms of PV_{ds} , the pre-tax excess which is available for the construction of the thermal distribution system, which is a determinant of HAHP-ICES economic feasibility). The heating- and cooling-load configuration (hence total gas and electricity usage) was held constant with respect to the base case, as were all other variables, in order to provide a meaningful basis for comparison.

The following seven cities were selected for this analysis: Atlanta, Cleveland (the assumed base-case city for energy rates), Kansas City, Chicago (the base-case city for load configuration), St. Louis, Minneapolis, and New York City. The cities were chosen to provide a range of high, average, and low energy costs as well as a range of electricity to gas cost ratios. The cities, the average energy costs, and the electricity-to-gas ratios computed for both systems (conventional and HAHP-ICES), along with the resulting values of PV_{ds} are presented in Table 4.6.

In Section 4.4.1, it was seen that, in general, higher energy costs yielded a greater excess available for the construction of the thermal distribution system. The rationale for this effect was explained in the following manner. The higher energy rates, which were applied equally and simultaneously to each component, provided for higher break-even annual energy

Table 4.5. IMPACTS OF GEOGRAPHIC LOCATIONS

	<u>Chicago</u>	<u>Minneapolis</u>	<u>Kansas City</u>	<u>Atlanta</u>
PV _{ds} *	\$31,586	\$46,598	\$20,443	\$15,408
Geographic Location	Midwest	North	Midwest	Southeast
(Census Region)	(East North Central)	(West North Central)	(West North Central)	(South Atlantic)
Climate Region	Temperate Continental (Warm Summer)	Temperate Continental (Cool Summer)	Temperate Continental (Warm Summer)	Humid (Subtropical)
Size of Office Building Relative to Base Case	1	1.4	0.86	0.91
Number of Degree Days Annually (Year)	HDD 6506.4 CDD 809.8 (1952)	HDD 7997.1 CDD 674.0 (1956)	HDD 4811.6 CDD 1609.0 (1957)	HDD 2827.3 CDD 1717.6 (1955)
Average Degree Days (Time Period)	HDD 6557.5 CDD 753.9 1949-1957	HDD 7964.3 CDD 704.6 1955-1964	HDD 4849.3 CDD 1686.7 1949-1958	HDD 2825.6 CDD 1717.3 1949-1958

* Dollars available for thermal distribution system. Base Case (Cleveland) energy rates used. Does not include impact of distribution system thermal losses.

Table 4.6. THE IMPACT OF VARIOUS RATE SCHEDULES ON BASE-CASE RESULTS

	<u>Atlanta</u>	<u>Cleveland</u>	<u>Kansas City</u>	<u>Chicago</u>	<u>St. Louis</u>	<u>Minneapolis</u>	<u>New York City</u>
PV _{ds} *	\$23,413	\$31,586	\$45,283	\$61,926	\$67,441	\$71,027	\$125,740
<u>Conventional System</u>							
Electric-To-Gas Ratio	7.38	3.82	8.10	5.08	4.64	4.82	7.72
Average Gas Cost, \$/10 ⁶ Btu	.93	2.02	1.28	2.23	2.12	2.21	3.23
Average Electricity Cost, \$/10 ⁶ Btu	6.85	7.72	10.39	11.30	9.84	10.63	24.90
<u>HAHP-ICES</u>							
Electric-To-Gas Ratio	19.91	7.5	19.85	10.3	6.56	8.71	14.72
Average Gas Cost, \$/10 ⁶ Btu	.87	2.02	1.21	2.12	2.10	2.15	3.45
Average Electricity Cost, \$/10 ⁶ Btu	17.33	15.17	24.02	21.81	13.77	18.70	50.81
Increase of <u>HAHP-ICES</u> Electricity Over Conventional, %	152	96	132	93	40	76	104

*

System surplus available for distribution system construction.
Does not include impact of distribution system thermal losses.

charges being supported by the office and residential components. Because the HAHP-ICES thermal utility consumes less energy than the conventional systems it replaces, the revenue increase more than offsets the increased energy costs applicable to the HAHP-ICES thermal utility.

With this in mind, it was anticipated that the New York City rate schedules (with the highest average gas and electricity costs of the selected cities) would yield the greatest value of PV_{ds} , and the Atlanta rate schedules (which yielded the lowest combined HAHP-ICES and conventional average gas and electricity costs) would provide for the smallest value of PV_{ds} within the group of selected cities. The results confirmed this reasoning with one exception: St. Louis, with an average electricity cost that falls below the mean of the selected cities, was expected to rank lower in terms of PV_{ds} than what actually resulted. This can be explained by the degree of rate-stepping that is employed by the various electric utilities. The electric utilities that service these cities each use demand-and-consumption rate steps in their billing computations. These rate steps result in a lower unit energy cost for large-volume electrical users and, conversely, a higher unit cost of electricity for low-volume users. Hence, because the HAHP-ICES thermal utility is a low-volume user in comparison with the office building, it pays a correspondingly higher per unit electric rate, which will result in a lower value of PV_{ds} . Thus, a low degree of rate-stepping provides for a smaller percentage increase in the average cost of electricity resulting from the implementation of the HAHP-ICES with respect to the conventional system's cost, and is thus favorable to the HAHP-ICES. Conversely, a high degree of rate-stepping is penalizing to the system. For example, within the group of selected cities, the percentage increase in the average cost of electricity to the HAHP-ICES thermal utility when compared with the conventional system's rates, ranges from a high of +152% (Atlanta) to a low of +40% (St. Louis). Because the St. Louis electrical rate-steps were more favorable to the HAHP-ICES thermal utility than the Chicago rate-steps, i.e., a flatter rate schedule, the former's value of PV_{ds} was relatively greater than the latter's even though energy costs were higher in Chicago than in St. Louis.

4.4.4 The Impact of Distribution System Losses on the Base-Case Results

Thermal losses associated with the distribution system are by nature site- and community-specific (dependent upon the community configuration, length of piping runs, climatic conditions, construction codes, etc.). Their effect on the economic viability of the general application of the HAHP-ICES concept is therefore, best evaluated by the use of sensitivity analysis techniques. Thermal losses would, of course, be reflected in a higher metered energy requirement to the central plant, and consequently, a higher annual energy cost for the HAHP-ICES thermal utility. Therefore, the annual cost of the gas consumed by the HAHP-ICES central plant was appropriately varied corresponding to five levels of assumed thermal distribution losses (as a percentage of the thermal load); no losses (the base case), 5%, 10%, 15%, and 20%. As usual, all other variables were held constant with respect to the base case. Certain underlying assumptions in the determination of these losses warrant consideration: First, thermal losses which occur in heating and cooling the office space are assumed to be zero because the corresponding distribution piping is routed within the conditioned space thereby displacing an equivalent portion of the respective

space conditioning load. Second, all thermal losses are offset by a boiler with an assumed efficiency of 83%. Third, the potential for using excess turbine condenser heat or the more efficient heat pump to compensate for the heat losses associated with supplying the space heating and domestic hot water load to the residential units has been ignored. Thus, the analysis presented is conservative, and the impact of the thermal losses may be overstated. Table 4.7 displays the additional loads and metered energy requirements corresponding to various thermal loss rates that were selected for evaluation, while Table 4.8 exhibits the effect of these losses on the base-case results.

In Table 4.8, we see that the cost of the additional energy required to offset the thermal losses associated with the distribution system reduces the system surplus, PV_{ds} , at each level of assumed heat loss. This occurrence is to be expected because the annual costs of the HAHP-ICES thermal utility are rising without a corresponding increase in their annual revenues. An assumed 15% thermal loss would be reflected in an approximate 15% reduction in PV_{ds} from the base-case level. Similarly, a 10%, 15%, and 20% thermal loss would yield an approximate 31%, 46%, and 62% reduction in the base-case system surplus, respectively. In Section 3.4.2, it was stated that the thermal losses encountered in supplying heating and domestic hot water to the apartment complex would approximate 6.1%. This figure is based on calculated heating and domestic hot water thermal distribution losses of 3.69×10^8 Btu/yr and a total heating and domestic hot water thermal load of 6.0×10^9 Btu/yr. Based upon our assumed boiler efficiency of 83%, an additional 444×10^6 Btu of natural gas would be required by the central plant to offset these thermal losses at a cost of \$897 per year. The life-cycle cost of this expenditure would be \$5,617, necessitating a system surplus of \$50,617 for a "viable" application in order to defray the cost of the distribution system and accommodate the increased energy costs of the HAHP-ICES thermal utility. Let us again reemphasize our functional definition of economic viability. In order for any application of the HAHP-ICES concept to be viable, three criteria must be met. First, the sum of the annual thermal energy charges assessed by the HAHP-ICES thermal utility to individual community members must at most be equal to the life-cycle cost of owning and operating individual conventional HVAC systems. Second, the owner of the HAHP-ICES thermal utility must earn a 15% pre-tax rate of return on its investment. Third, the system surplus (including the effect of thermal losses), PV_{ds} , must be sufficient to defray the life-cycle cost of the thermal distribution system.

It may be noted that thermal losses of between 10% and 20% of the total thermal load are commonly reported based on European district heating experience. However, these estimates lack the supportive information (such as the degree of insulation, system configuration, materials, etc.) that would be necessary to establish their validity for a given distribution network in a functional application. The range of losses presented in this sensitivity analysis should give some insight into their impact of the base system's economics.

Table 4.7. THE IMPACT OF DISTRIBUTION SYSTEM LOSSES ON METERED ENERGY CONSUMPTION IN THE BASE CASE

Percentage Loss [*]	Additional Load Resulting From Heat Loss (Btu/yr)	Compensatory Metered Energy at 83% Efficiency (Btu/yr)
5%	3.1918×10^8	3.8455×10^8
10%	6.3836×10^8	7.6911×10^8
15%	9.5754×10^8	1.1537×10^9
20%	1.2767×10^9	1.5382×10^9

* As a percentage of total thermal load for residential space heating and domestic hot water.

Table 4.8. THE IMPACT OF DISTRIBUTION SYSTEM LOSSES ON THE BASE-CASE RESULTS

Percentage Loss [†]	Additional Metered Energy Required to Offset Thermal Losses* (10^6 Btu/yr)	Annual Increase in Energy Cost,* \$	Total Discounted Increase [*] in Energy Costs,** \$	Resultant System Surplus (PV _{ds}), \$
0%	-0-	-0-	-0-	31,586
5%	384.55	776.79	4,861.92	26,724
10%	769.11	1553.61	9,724.05	21,862
15%	1153.70	2330.47	14,586.41	17,000
20%	1538.20	3107.16	19,447.72	12,138

* For HAHP-ICES thermal utility.

** The present value of an annuity at 15% for 20 years.

† As a percentage of thermal loads for residential space heating and domestic hot water.

The results of this analysis reveal the significance of the tradeoff between the cost associated with reducing the thermal losses of the distribution system (via distribution piping with reduced heat transfer characteristics, etc.) and the life-cycle increase in the cost of energy required to compensate for a given level of thermal losses. In the base-case system, which assumes constant energy rates, if you can reduce the thermal losses of the distribution system by five percentage points for less than \$4,862, it is economically prudent to do so, and to continue to do so until it is no longer possible (within these constraints). Naturally, if the energy costs were assumed to be rising over the project life, the maximum feasible expenditure to achieve this loss reduction would be significantly greater.

4.4.5 Community Density

In this analysis, two factors were examined: 1) the distance from the office building to the residential complex, and 2) the density of the residential complex in terms of the number of buildings. The densities chosen for analysis were: one building having 120 units, three buildings having 40 units each, and the base case of five buildings having 24 units each. For all cases the system loads were assumed to be the same and the building spacing for the three-building case was identical to the five-building case.

As can be seen in Table 4.9, which shows the results of this analysis, increasing community density decreases the distribution system costs, and increasing the distance between the office and residential complex increases the distribution system cost. Because our economic model solves for the amount which would be available to defray the cost of the distribution system, the results of the preceding sensitivity analyses can be compared with these costs to identify economically feasible community densities.

Table 4.9. EFFECT OF COMMUNITY DENSITY ON THE DISTRIBUTION SYSTEM COST

Distance Between Office and Residential Complex, ft	Number of Residential Buildings		
	1	3	5
	Distribution System Cost,* \$		
200	8,500	25,500	37,500
400	15,750	33,000	45,000**
600	28,250	45,000**	57,250
800	37,250	54,500	66,250
1,000	46,250**	63,500	75,250
1,200	64,250	81,250	93,250
1,400	74,750	92,000	104,000
2,000	85,250	102,500	114,500

* Rounded to the nearest \$250. Does not include impact of distribution system thermal losses.

** Comparative density equivalents to the base case with respect to the cost of the distribution system.

4.4.6. Summary of Sensitivity Analyses

The following listing displays factors which were identified in the sensitivity analyses as having a favorable impact upon the economics of the HAHP-ICES. For the most part, they are presented here without a detailed rationalization of their economic effects, as a convenience to the reader of this section; however, a detailed explanation of how each element specifically affects the economics of the HAHP-ICES can be found in Subsections 4.4.1, 4.4.2, 4.4.3, 4.4.4, and 4.4.5 (which discuss the impact on system economics of economic variables, geographic location, energy rate schedules, distribution system losses, and community density, respectively).

- Higher discount rates for the residential and office components.
- Higher interest rates for the residential and office components.
- A lower interest rate for the HAHP-ICES thermal utility.
- Lower capital requirements for the implementation of the HAHP-ICES.
- Decreases in the operating and maintenance requirements of the HAHP-ICES.
- Increases in the cost of energy, both relative to inflation and in the price of gas relative to the price of electricity.
- Climates featuring a heat load of sufficient duration and a sufficient number of heating-degree-days to take advantage of the HAHP-ICES heat pumping efficiency. For example, in the analysis of the impact of geographic locations on the economics of the HAHP-ICES with the base-case community, Minneapolis and Chicago with 8000 and 6500 (approximately) annual heating-degree-days, respectively, demonstrated an economic superiority to Kansas City and Atlanta, with 4800 and 2800 annual heating-degree-days, respectively.
- High energy rates in combination with a low degree of rate stepping (the effective penalty [higher rates] for low volume electrical consumers, such as the HAHP-ICES thermal utility). When cities were compared on the basis of rate schedules, the rate schedules for Minneapolis, St. Louis, and Chicago yielded a system surplus in excess of that required for the construction of the thermal distribution system primarily because the degree of rate stepping by electrical utilities in these cities was relatively low. New York City, in contrast, demonstrates the relationship between high energy rates and the favorability of the HAHP-ICES by ranking first within the group of selected cities even though it ranked fifth out of seven cities in terms of a high degree of rate stepping.
- Lower thermal losses from the distribution system. The optimal level of thermal loss reduction must be identified. This optimal level occurs at the point where the cost of modifying the thermal distribution system to reduce thermal losses exceeds the value of the energy saved by doing so.

- High community density. A greater community density, in terms of the distance between the community members and/or number of community members, translates into a lower cost for the thermal distribution system and lower associated thermal losses. Caution must be exercised not to reduce community membership beyond an optimal point for the utilization of the HAHP-ICES central plant's load potential with respect to its plant and equipment cost.

The purpose of this section has been to evaluate general applications of the HAHP-ICES concept in terms of their economic feasibility. Economic feasibility in the context of this report has been defined as the meeting of three primary objectives: First, the summation of the annual thermal energy charges assessed to each community member must at no time exceed the life-cycle cost of owning and operating their individual, conventional HVAC systems. Second, the owner of the HAHP-ICES thermal utility is to earn a 15% pre-tax rate of return on any assumed investment. Prior to the statement of the third objective, certain fundamental concepts must be restated. In order to obtain empirical performance data, a base-case community was defined. Cleveland energy rates and Chicago climatic data were chosen to provide a starting point for the economic assessment of general applications of the HAHP-ICES concept. The model employed to evaluate each application solved for an amount which would be incurred during the system's lifetime. Which leads to the final (third) objective: The system surplus must be sufficient to defray the cost of the thermal distribution system. If the system surplus exceeds the amount necessary for the thermal distribution system, the remainder would be "returned" to the community members in the form of a reduction in their annual thermal energy charges.

The base-case concept, as defined, does not yield a sufficient system surplus to meet our financial objectives. This outcome in itself is less significant than the true purpose of the base case, which is to function as a reference point for the sensitivity studies that followed. The sensitivity analyses identified applications of the HAHP-ICES that met and exceeded (in the sense that a portion of the system surplus could be returned to the community members) the stated objectives. Moreover, the factors that impacted on the base case and resulted in a feasible application are currently realistic — escalating energy rates (instead of the static rates assumed in the base case), different geographic locations (similarly, community load variations), and different energy rate schedules.

The analyses indicate that the overall economic outlook for applications of the HAHP-ICES concept is positive. Factors which may be varied can be used to tailor the HAHP-ICES to a given site. With this in mind, a method was selected to provide the reader with some insight into how the base-case application of the HAHP-ICES concept may be altered to achieve economic feasibility in site-specific applications throughout the United States. This method, although qualitative in nature, serves to combine what was learned in the individual sensitivity analyses to act as a useful guide for HAHP-ICES community design.

Figure 4-1, which depicts the contiguous United States divided into nine Census Regions* and four climatic regions, was the starting point for this analysis. Regional averages for energy prices (gas and electricity) were computed and compared with those of the East North Central Region (the base-case reference location) and a percentage rate of change was noted. Because statewide price averages were used to develop multi-state regional energy price averages, the percentage change does not reflect the considerable variations which occur in local markets. For purposes of simplicity, the contiguous United States was divided into four climatic regions based on a range of heating-degree-days. Climatic Region 1 was defined as those areas experiencing more than 7000 heating-degree-days, while Climatic Regions 2, 3, and 4 were established with limits of 7000 to 5000, 5000 to 3000, and less than 3000 heating-degree-days annually. Certain areas of the country were eliminated from this analysis due to a wide range of climatic variations present within relatively small areas (e.g., California), or because of an insufficient number of annual heating-degree-days to merit consideration (e.g., the southern tip of Texas).

Given these regional energy rates and climatic conditions, we examined the possibility of varying three factors in order to obtain economic results equivalent to those of the base-case analysis. A rating system was developed to indicate a possible course of action and the magnitude (great, moderate, or minimal) of the required adjustment for each factor, independent of the other two. The rating scale runs from -3 to +3, with the absolute value of the term indicating the magnitude of the required change, and the sign indicative of whether a reduction (-) or an increase (+) in that factor is warranted. The factors considered in this analysis are:

- Residential Community Size. Variations in the number of residential buildings in a community with respect to the base case (five residential and one office building). For example, a positive rating is interpreted to mean that an increase in the number of residential buildings would be required in that region if economic results equivalent to those of the base case were desired. A negative rating indicates that the number of residential buildings could be decreased if desired.
- Density. Variations in the apparent community density with respect to the base case or its equivalent. As was noted in Table 4.9 (The Effect of Community Density on the Distribution System Cost), three base-case equivalent (~\$45,000) distribution system costs were generated. Thus, density-wise, the one-building case at 1000 feet, is equivalent to the three-building case at 600 feet, which is equivalent to the base case of five buildings with a distance of 400 feet between the residential complex and the office building. If these three cost figures were connected with a line, the area above the line would include those areas with a greater density than the base case; the area below would include those areas with a lesser density. A negative rating for the factor indicates an option for decreasing community density while a positive rating indicates a need for increased community density in order to have an economical system.

* United States Bureau of the Census statistical area.

REGION	HEATING DEGREE-DAYS
1	>7000
2	7000-5000
3	5000-3000
4	<3000

Figure 4.1. THE CONTIGUOUS U.S. FEATURING CENSUS AND CLIMATIC REGIONS

- Distribution System Losses. Variations in the level of thermal losses associated with the distribution system from the base case level (15%). A negative rating would indicate that a reduction in the thermal losses (from 15%) is required to achieve base-case result parity, and a positive rating signifies that an increase in thermal losses is acceptable if economic results equivalent to the base case are desired.

Table 4.10 presents the Census Regions (typifying energy rates); the climatic classifications; and the associated rating terms for the size of the residential community, density, and distribution system losses. Although achieving results which are equivalent to those of the base case was our stated objective, alternatives that can yield superior results are an inferential by-product of this study. For example, for New England (Climatic Region 1), the -3 rating for density indicates that the community density can be significantly reduced and still result in base-case parity. However, this is also indicative of the fact that if the community density is kept at the base-case level, the economic results will be significantly superior to those of the base case. Hence, this analysis presents the latitudes and constraints which affect the options available to the designer of a HAHP-ICES application within the bounds of energy rates and climate. When the ratings indicate either decreasing the residential community size, decreasing density, or increasing distribution system losses, the prudent designer would opt not to alter these factors and maximize the economic feasibility of the application. However, if site-specific limitations necessitated a change in those factors, the flexibility exists to do so.

4.5 Site-Specific Application

The purpose of this section is to report on the economic feasibility of the HAHP-ICES in an expanded, site-specific community application. Economic feasibility is once again defined as meeting the return requirements of the owners of the HAHP-ICES central plant (which is hereafter referred to as the HAHP-ICES thermal utility), while simultaneously ensuring that all other community members maintain the same level of profitability as could have been obtained had a conventional HVAC system been installed.

The site-specific community is composed of: a townhouse component consisting of 42 units, a low-rise residential component consisting of five buildings having a total of 120 rental units, a high-rise residential component composed of five buildings each having 104 rental units, an office component consisting of a single building sized at 124,000 ft², and a retail component consisting of a single, 135,000 ft² building.

Thermal loads for heating and cooling in the site-specific application of the HAHP-ICES concept are based upon weather data obtained for Monroeville, a suburb of Pittsburgh, Pennsylvania. Energy charges are based upon Pittsburgh rates.

The methodology used in the analysis of the site-specific case is that which has been presented in Section 4.1. The site-specific analysis differs from the base-case (general application) analysis only in the number (and

Table 4.10. QUALITATIVE ASSESSMENT OF THE HAHP-ICES CONCEPT
IN DIFFERENT REGIONS OF THE CONTIGUOUS UNITED STATES*

<u>Census Region</u>	<u>Change in Energy Costs From Base-Case Region, %</u>	<u>Climate</u>	<u>Residential Community Size</u>	<u>Density</u>	<u>Distribution System Losses</u>
New England	+57.2	1	-1	-3	+2
		2	-1	-1	+1
Mid-Atlantic	+37.8	1	-1	-2	+1
		2	-1	-1	+1
South Atlantic	+2.9	3	+2	+2	-2
		4	+3	+3	-3**
East North Central	-0-	1	-1	-1	+1
	(base-case)	2	0	0	0
East South Central	-21.6	3	+3	+3	-3**
		4	+3**	+3**	-3**
West North Central	-18.2	1	0	0	0
		2	+1	+1	-2
West South Central	-15.5	3	+2	+2	-3
		4	+3	+3	-3**
Mountain	-26.7	1	0	0	0
		2	+1	+1	-2
		3	+3	+3	-3**
Pacific	-17.3	1	-1	-1	+1

* The qualitative rating system indicates the magnitude of change from the base-case assumptions; significant (3), moderate (2), minimal (1), and no change (0). The sign is indicative of the direction of change; a reduction is denoted with a negative sign (-), an increase is denoted with a positive sign (+).

** Varying this factor alone would not result in economic parity with respect to the base case.

type) of community members served by, and hence the composition of the revenues of, the HAHP-ICES thermal utility.*

4.5.1 Site-Specific Case

The economic evaluation of the HAHP-ICES in the site-specific application was based on the treatment of each community member as an independent entity. Specifically, the townhouses (42 units), the low-rise residential complex (consisting of five buildings), the high-rise residential complex (consisting of five buildings), the office building, the retail building, and the HAHP-ICES thermal utility are treated as separately-financed, independent operations.

In order to determine the amount of the annual thermal energy charge which the HAHP-ICES thermal utility could assess to each community member, a differential life-cycle cost comparison was made between a conventional HVAC system and the HAHP-ICES. For each member, the timing and amount was determined for those costs which would not be incurred if the HAHP-ICES was chosen over a conventional system. The costs included differential values for: The investment in necessary HVAC equipment; annual operating and maintenance; primary energy (gas and/or electricity); insurance and property taxes; and income tax effects. Each component member of the site-specific community was assumed to be financed through mortgages under the conditions presented in Table 4.11. The amount and timing of all costs were projected for the lifetime of the system, discounted back to a base year (the first year of system operation), and then annualized into level payments. The maximum annual thermal energy charge by the HAHP-ICES thermal utility to each community member was set equal to these levelized annual payments.

The HAHP-ICES thermal utility was assumed to have revenues equivalent to the summation of the annual thermal energy charges from the community it serves. The HAHP-ICES thermal utility was assumed to require a 15% pre-tax rate-of-return on any acceptable project. This value coincides with the current experience of the five most profitable large utilities in the United States. If the HAHP-ICES is to be an attractive venture, it should yield as high a rate-of-return as that which is currently realized by the most profitable utilities from conventional operations. The financing of the HAHP-ICES thermal utility was assumed to be standard utility with equal-load, annual amortization payments. The following chart describes the basic assumptions:

HAHP-ICES Thermal Utility

Life (no salvage), years	20
Loan, %	75
Interest, %	10
Depreciation	DDB w/switch**
Depreciation Bonus	no
Insurance, %	1
Property Tax, %	1

* For a complete presentation of the equations employed in the economic analyses, see Section 9.5.

** Double declining balance with switch to straight-line in Year 11.

Table 4.11. COMPONENTS OF SITE-SPECIFIC COMMUNITY
(EXCLUDING HAHF-ICES THERMAL UTILITY)

Type and Description	Life (Years)	Mortgage %	Interest %	Depreciation	Depreciation Bonus	Insurance, % of Investment	Property Tax, % of Investment	Tax Rate
Townhouse [†] 42 Units	20	80	8	DDB w/Switch*	Yes	1	1	50
Low-Rise Residential 5 Buildings 24 Units Per Building 120 Total Rental Units	20	80	8	DDB w/Switch*	Yes	1	1	50
High-Rise Residential 5 Buildings 104 Units per building 520 Total Rental Units	20	75	10	DDB w/Switch*	Yes	1	1	50
Office 1 Building 124,000 sq ft	20	75	10	DDB w/Switch*	Yes	1	1	50
Retail 1 Building 135,000 sq ft	20	75	10	DDB w/Switch*	Yes	1	1	50

* Double declining balance with switch to straight-line in year 11.

† Townhouses are owned as rental property, qualifying for business expenses.

The allowable annual thermal energy charges for community members served by the HAHP-ICES thermal utility were determined using after-tax current value calculations with an 8% discount rate. The determination of the economic condition of the HAHP-ICES thermal utility was made by calculating the current value of the pre-tax excess revenues over the various cash and non-cash costs and the equity investment, using a 15% discount rate. The non-cash expenses (depreciation) and non-expense items (amortization of the debt and the equity investment) were adjusted to a pre-tax basis. The current value of the pre-tax excess represents the total capital cost which would be allowed for the thermal distribution system. When this excess, PV_{ds} , surpasses the life-cycle cost of the distribution system, the remainder can either be returned to the community members in some equitable manner, or accrue to the owner of the HAHP-ICES thermal utility as a higher rate of return. Throughout this analysis, the former assumption is presumed to occur.

For the site-specific community configuration presented as Figure 1.17 in Section 1 (Community Description), a thermal distribution system cost of \$385,000 has been estimated. Section 9.6 presents the basis for this estimate.

Costs assumed in the site-specific case are shown in Tables 4.12 and 4.13 with the bases upon which these costs were developed shown in Section 9.4 (System Costing).

The results of the economic analysis of the site-specific case are displayed in Table 4.14. They reveal that a sufficient pre-tax system surplus (PV_{ds}) exists in each of the four cases presented (0 through 4 turbines) to meet the definition of economic feasibility previously established for the HAHP-ICES concept. Specifically, each criterion of economic feasibility is being met. First, each community member served by the HAHP-ICES thermal utility is in the same financial position as they would have been had they chosen individual conventional HVAC systems. Second, the owner of the HAHP-ICES thermal utility is earning a 15% pre-tax rate-of-return on the investment in the HAHP-ICES central plant. Third, a pre-tax system surplus exists in each case that sufficiently defrays the life-cycle cost of the thermal distribution system, which for the site-specific case has been estimated at \$385,000. Note that it is assumed that the normal operating and maintenance expenses associated with the distribution system have been included in the annual operating and maintenance expenses of the HAHP-ICES central plant.

The zero turbine case, which is essentially a highly efficient conventional district heating system yields a system surplus of \$520,112, of which \$385,000 is necessary to offset the life-cycle cost of the thermal distribution system. The remaining \$135,112 can be "returned" to the community members served by the HAHP-ICES thermal utility in the form of a reduction in their assumed annual thermal energy charges. If we were to equate the system surplus with the life-cycle cost of the distribution system, a 5% reduction in the community members' annual thermal energy charges would be warranted. Similarly, maximum reductions of 4.4, 2.6, 1.5, and .01% would result in this equilibrium for the remaining (1-4) turbine cases, respectively. Since the original annual thermal energy charges equated the life-cycle costs for owning and operating a conventional HVAC system with the HAHP-ICES for each community member, the reduced annual thermal energy charges represent a real

Table 4.12. COSTS ASSUMED FOR HAHP-ICES THERMAL UTILITY IN THE SITE-SPECIFIC CASE

<u>Number of Turbines</u>	<u>Installed Costs</u>	<u>Annual Operating and Maintenance (First 10 Yrs)</u>	<u>Annual Operating and Maintenance (Second 10 Yrs)</u>	<u>Energy Costs*</u>
0	\$655,244	\$57,319	\$66,399	\$178,023
1	\$724,855	\$58,329	\$67,912	\$169,132
2	\$793,137	\$59,328	\$69,411	\$165,096
3	\$859,134	\$50,333	\$70,917	\$158,665
4	\$926,456	\$51,334	\$72,419	\$153,806

* Disregarding thermal losses from distribution system.

Table 4.13. COSTS ASSUMED IN THE ECONOMIC ANALYSIS OF THE SITE-SPECIFIC CASE

<u>Building Type</u>	<u>Decrease in Building Cost*</u>	<u>Yearly Decrease Annual O & M**</u>		<u>Annual Energy Cost With a Conventional System†</u>
		<u>First 10 Years</u>	<u>Second 10 Years</u>	
Townhouse Apartment (42 Units)	\$11,109	\$2,170	\$2,170	\$10,337
High-Rise Residential (520 Units)	\$579,325	\$25,000	\$30,250	\$114,300
Low-Rise Residential (120 Units)	\$80,070	\$6,200	\$6,200	\$24,008
Office (124,000 ft ²)	\$229,500	\$12,400	\$15,500	\$36,485
Retail (135,000 ft ²)	\$201,825	\$13,200	\$16,500	\$30,167

* Initial reduction in required HVAC equipment resulting from implementation of HAHP-ICES concept.

** Annual reduction in operating and maintenance expenses resulting from implementation of HAHP-ICES concept.

† Annual reduction in energy costs for conventional heating and/or cooling, displaced as a result of the implementation of HAHP-ICES concept.

Table 4.14. RESULTS OF THE ECONOMIC ANALYSIS OF THE
SITE-SPECIFIC CASE - FULL SITE-SPECIFIC COMMUNITY*
(Constant Energy Costs)

<u>Number of Turbines</u>	<u>PVds, \$**</u>	<u>Potential Cost Savings, %[†]</u>
0	520,112	5.1
1	502,446	4.4
2	455,735	2.6
3	426,159	1.5
4	385,497	0.019

* Full Site-Specific Community Consists of:

- A townhouse component consisting of 42 units
- A low rise component consisting of 5 buildings, 120 total units
- A high rise component consisting of 5 buildings, 520 total units
- An office component consisting of 1 building sized at 124,000 sq ft
- A retail component consisting of 1 building sized at 135,000 sq ft.

** System surplus available to defray the life-cycle cost of the thermal distribution system (assuming normal operating and maintenance expenses are included in HAHP-ICES central plant's annual O&M expense). Does not include impact of distribution system thermal losses.

† Potential annual savings to HAHP-ICES community members in the cost of owning and operating individual conventional HVAC equipment.

economic incentive for the HAHP-ICES. In the one turbine case, the HAHP-ICES would offer each community member a 4.4% annual reduction in the costs associated with owning and operating a conventional HVAC system.

There are two reasons why the zero turbine case (essentially a conventional district heating system) yielded the greatest system surplus among the cases examined. First, the cost of the turbine, components necessitated by the addition of each turbine, and the associated operating and maintenance expenses exceed the respective costs of the conventional equipment selected for the zero turbine case. These turbine related costs tend to offset the greater energy efficiency (measurable in decreased energy consumption) realized through their addition to the HAHP-ICES central plant. Secondly, as was noted in the base-case analysis, the "rate-stepping" practice of the electric utilities effectively penalizes the HAHP-ICES thermal utility by charging higher rates as electrical consumption decreases. Table 4.15 illustrates this point.

Table 4.15. COMPARISON OF UNITS COSTS OF ELECTRICITY
AS A FUNCTION OF CENTRAL PLANT TURBINES

<u>Number of Turbines</u>	<u>Quantity of Electricity, 10⁶ Btu</u>	<u>Total Cost of Electricity, \$</u>	<u>Cost per 10⁶ Btu of Electricity, \$</u>
0	3,095	55,778	18.02
1	1,970	49,883	25.33
2	1,484	44,932	30.28
3	1,152	40,496	35.16
4	900	36,517	40.57

Notice that when we add the first turbine, electrical consumption decreases by 36%, while the total cost of that electricity decreases by less than 11%. The effective penalty implicit in such a rate structure is sufficient in itself to alter the ranking of these cases in terms of the resultant system surplus. For example, in the previous analysis of the site-specific case, which uses the actual electric rates of the Duquesne Light Company, the zero turbine case yielded the greatest system surplus while each successive turbine addition resulted in a lesser surplus than the preceding case. If we now assume an identical unit cost of electricity in each of these cases, the ranking of these cases from greatest system surplus to least (stated in number of turbines) would be: the one, two, three, zero, followed by the four turbine case. Hence, it is clearly demonstrable that the current electric rate structures prevent the energy efficiencies explicit in the HAHP-ICES from fully impacting on the generated system surplus in a beneficial way.

4.5.1.1 Sensitivity Analysis on the Site-Specific Case

The economic analysis of the site-specific case to this point, has assumed that energy costs (as well as all other costs) are quoted in current (1979) dollars and held level over the life of the project. In this way, the results can be corrected for the influence of general inflation in any given year by using the appropriate price index. The following analysis was performed to examine the effects on the system surplus results of the site-specific case of energy costs which are rising faster than the rate of general inflation. Yearly escalation factors of 4.32% for gas costs, and 1.38% for electric costs were chosen based on a "weighted average"* of projected energy prices by the American Gas Association and the U.S. Department of Energy.⁶

As discussed previously, escalating energy rates, in general, improve the overall economic performance of the HAHP-ICES. This is due, in part, to the ability of the HAHP-ICES central plant to displace more energy than it consumes when replacing the conventional HVAC equipment of the community it serves. The reader is referred to the discussion in Section 4.4.1 on the cost of energy (relative to inflation).

* Assigning a weight of .667 for the A.G.A. estimate and .333 for the DOE estimate.

We saw that in the original analysis of the site-specific application of the HAHP-ICES concept, the zero turbine case yielded the greatest system surplus among the cases presented even though the energy consumption by the HAHP-ICES thermal utility decreased with the addition of each turbine. The combined effects of higher turbine associated costs (when compared with conventional HVAC equipment) and penalizing electric rate structures were offered as an explanation of the results. However, at some point (assuming annual escalations in energy costs) the reduction in the energy consumption of the HAHP-ICES central plant obtained through the addition of turbines, must generate energy cost savings which offset disadvantageous cost or rate situations. This reasoning will be confirmed if the case-rankings (in terms of the amount of system surplus generated) change in favor of the turbine systems, or if the difference in the system surplus between the zero and the one or multiple turbine cases has diminished. [Remember that it was stated at some point the turbine cases would yield a greater surplus, but that point may be beyond the level of our chosen (4.32% gas and 1.38% electricity) annual escalations.]

The results of annually escalating energy rates on the results of the site-specific case are displayed in Table 4.16. The zero turbine case now yields a system surplus of \$665,378, while the one turbine case has a generated surplus of \$657,378. The difference between these two results has decreased to \$7,852 from a previous level of \$17,666 (a 55.55% reduction) in the analysis assuming constant energy rates. Similar, but not as dramatic decreases in the system surplus differentials between the cases with, and without, escalating energy rates are experienced. The reason why the percentage reductions are not as great again has to do with the "rate stepping" in the electric utility's rate structure. The percentage increase in the electric rates as we add turbines (and decrease electricity consumption) exceeds the percentage decrease in the quantity of electricity consumed. Hence, the higher rates are partially offsetting the energy efficiency potentials of the multiple turbine systems.

The values of the system surpluses generated in each of the cases (Table 4.16) exceed the \$385,000 estimate for the thermal distribution system. Hence, the HAHP-ICES thermal utility is again in the position to offer potential savings in the cost of owning and operating conventional HVAC systems to the community members it serves. The amount of these savings in the annual thermal energy charges to community members would be roughly 9.1% for the zero turbine case, 8.8% for the one turbine case, and 7.3%, 6.6%, and 5.4% for the two through four turbine cases, respectively.

Before the issue of thermal losses from the distribution system is discussed, the rationale for our presentation of two sets of results for the site-specific case is warranted. So far, the results of this section have been presented under two assumptions: First, where energy costs are held constant over the project's life, thereby simulating a scenario where all costs are increasing at the rate of general inflation; and second, under the assumption that energy rates are escalating at some chosen level above the rate of general inflation annually. But, which set of results more accurately reflects the expected economic performance of each application of the HAHP-ICES concept?

Table 4.16. THE IMPACT OF ANNUALLY ESCALATING ENERGY COSTS^{*}
ON THE RESULTS OF THE SITE-SPECIFIC CASE

<u>Number of Turbines</u>	<u>PVds, \$**</u>	<u>Potential Cost Savings, %†</u>
0	665,378	9.1
1	657,526	8.8
2	611,786	7.3
3	589,038	6.6
4	552,572	5.4

* Yearly escalations of 4.32% assumed for gas, 1.38% for electricity (above general inflation), based on a weighted average of energy projections from the American Gas Association and the U.S. Department of Energy.*

** System surplus available to defray the life-cycle cost of the thermal distribution system (normal O&M expenses are included in the HAHP-ICES central plant's annual operating and maintenance expense). Does not include impact of distribution system losses.

† Potential annual savings to community members served by HAHP-ICES thermal utility in the cost of owning and operating individual, conventional HVAC systems.

Considering the preponderance of projections and predictions supportive of the latter assumption, the site-specific case results, incorporating the use of escalating energy rates, should be thought of as the more realistic of the two cases. If the supra-general inflation escalating energy scenario is more likely, why were the other results presented? The results of the site-specific case with static energy rates were presented to provide an ultra-conservative perspective for the evaluation of the economic feasibility of the HAHP-ICES concept. This perspective simulated a "worst case" analysis because escalating energy rates are inherently beneficial to the economic assessment of a system such as the HAHP-ICES that consumes less energy than it displaces. However, because our chosen rates of energy escalation (4.32% for gas and 1.38% for electricity, annually) can be viewed as both conservative and more realistic considering the time-frame of this study, this dual presentation of results will no longer be continued.

Because thermal losses that are associated with the distribution system are a function of many variables (system configuration, heat transfer characteristics of construction materials, construction codes, etc.), some of which are under the control of the designer of the system, the issue of thermal losses was treated both specifically, from the site-specific thermal loss calculations presented in Section 3.5.2, and generally, in the form of a sensitivity analysis.

* Program Advisory Board (Meeting No. 5), DOE Contract No. EY-76-C-02-2883.

Heating losses are assumed to be offset through the use of a boiler with an efficiency of 83%. The benefit derived from the use of the more efficient heat pump or excess turbine condenser heat to offset heating or domestic hot water losses was ignored. Thermal losses in the cooling distribution system to the office, retail, and high-rise buildings are offset with a steam turbine-driven chiller with a COP of .88 (at an ambient temperature of 90°F), exclusive of parasitics.

Our calculated thermal losses from the heating and domestic hot water piping are 1.73×10^9 Btu/yr. Based on a total heating and domestic hot water load for all buildings of 4.11×10^{10} Btu/yr, on a percentage basis, this translates to an annual thermal loss of about 4.2%. Concurrently, our calculated cooling losses (thermal gains) are 7.96×10^6 Btu/yr. With a total cooling load of 1.12×10^{10} Btu/yr, this yields an annual percentage cooling loss (thermal gain) of approximately .07%.

From our assumptions and our calculated losses, an addition quantity of 2091×10^6 Btu of natural gas at a cost of \$4624 would be required by the central plant to offset these losses. Assuming escalating energy rates, PV_{ds} for the 0 to 4 turbine cases respectively now becomes \$626,642; \$618,790; \$573,050; \$550,302; and \$513,836. All of the turbine cases remain economically feasible, having a sufficient surplus to defray the life-cycle cost of the distribution system.

The sensitivity aspects of distribution losses was addressed by varying the annual cost of gas consumed by the HAHP-ICES thermal utility corresponding to five levels of assumed distribution thermal losses between 0% and 20%, in order to present the effect of the additional expense on the system's economics. The compensating metered energy requirements are shown in Table 4.17 and the economic results are presented in Table 4.18. The reader is cautioned when using these tables. For simplicity and consistency with the base-case analysis of distribution losses, a 5% loss is interpreted to mean 5% of the total heating and domestic hot water load and 5% of the total cooling load. Our calculations have shown the cooling losses (thermal gains) to be negligible (<.1%).

The tradeoff between the cost of modifying the distribution system to reduce thermal losses and the energy savings resulting from doing so becomes evident. If thermal losses can be reduced by five percentage points through distribution system modifications for less than \$59,478, the resultant energy savings would justify that expenditure, and additional like expenditures until those constraints can no longer be met. However, the lack of available data for commercially existent thermal distribution systems prohibits any further analysis of the tradeoffs involved, the attainable level of loss reduction, and the associative costs of distribution system modification.

Table 4.17. THERMAL LOSSES ASSOCIATED WITH THE DISTRIBUTION SYSTEM
(Site-Specific Case)

Percentage Loss	Compensatory Metered Energy For Heating Losses (10 ⁶ Btu)*	Compensatory Metered Energy For Cooling Losses (10 ⁶ Btu)**	Total Additional Energy (10 ⁶ Btu)	Additional Cost of Gas, Year 1 (\$)
5	2476.6	632.1	3108.7	6,873
10	4953.3	1264.2	6217.5	13,747
15	7429.9	1896.2	9326.1	20,620
20	9906.5	2528.0	12434.5	27,492

* Heating losses are assumed to be offset by a boiler with an efficiency of .83.

** Cooling losses are assumed to be offset with a steam turbine-driven chiller, with a COP of .88.

Table 4.18. THE IMPACT OF THERMAL LOSSES ON THE SITE-SPECIFIC CASE
(Escalating Energy Rates)*

Number of Turbines	Level of Thermal Losses				
	0%	5%	10%	15%	20%
0	\$665,378	\$607,802	\$550,217	\$492,640	\$435,072
1	\$657,526	\$599,949	\$542,364	\$484,787	\$427,219
2	\$611,786	\$554,209	\$496,624	\$439,048	\$381,479
3	\$589,038	\$531,462	\$473,876	\$416,299	\$358,731
4	\$552,572	\$494,996	\$437,411	\$379,834	\$322,266

* Assuming annual escalation of 4.32% for gas, 1.38% for electricity.

4.5.2 Cash Flow Analysis - Site-Specific Case

The preceding analysis employed a model which determined the annual thermal energy charges for the individual HAHP-ICES community members. These annual thermal energy charges were constrained to equate their lifetime HAHP-ICES costs with the cost of conventional HVAC system ownership. The thermal utility was then analyzed to determine whether a sufficient excess of life-cycle revenues over life-cycle costs existed to defray the life-cycle cost of the distribution system.

In this way, the life-cycle cost of the thermal distribution system was made the determinant of economic feasibility, and for good reason. In a general, non-site specific application, it is easier to envision a base-case reference community of buildings in a number of sites throughout the country, if one allows for the flexibility of altering the community's configuration. In that case, one only needs to recalculate the cost of the distribution system, compare this value to the generated system surplus, PV_{ds} , and determine if the application is economically feasible. This method also allows for the possibility of examining certain issues pertaining to the distribution system, such as modifications to reduce the level of thermal losses, etc. The resultant system surplus was also displayed for the site-specific case to provide a basis for comparison with the base-case presentation. However, it is now appropriate to undertake a detailed cash flow analysis of the site-specific application of the HAHP-ICES concept.

To avoid unnecessary complications, one basic assumption is made pertaining to the HAHP-ICES thermal utility. The HAHP-ICES thermal utility will be treated for tax and accounting purposes as an independent domestic corporation, solely organized to provide the space conditioning needs of our site-specific Monroeville community. The appropriate tax rate for after-tax cash flow calculations is based upon the taxable income generated annually by this corporation employing the actual federal tax rates as specified by the Revenue Act of 1978.* The thermal distribution system cost of \$385,000 now is added to the capital requirements of the HAHP-ICES thermal utility. As before, the HAHP-ICES thermal utility will finance 75% of the total project through debt, 25% through equity, and the 2% allowance for other annual costs (insurance and property tax) will also pertain to the cost of the distribution system. As stated in the previous section, the thermal losses from the distribution system will require that an additional 2091.045×10^6 Btu of natural gas be purchased annually (see Section 9.3, Energy Costs, for the energy costs employed), and the energy costs relevant to the HAHP-ICES thermal utility have been adjusted to reflect this fact.

For each of the 0 to 4 turbine cases, the annual cash flows were calculated on both a pre-tax and after-tax basis. These cash flows were then discounted until the summation of the discounted net cash flows were equal to the equity investment.

* Publication 6303, Commerce Clearing House Master Tax Guide (1979), see Section 9.5.4 for the tax table used.

The method of determining the return on invested equity capital (or capital at risk) produces a result which is most commonly referred to as the Discounted Cash Flow Rate of Return (DCFROR). Other names commonly used for DCFROR are Profitability Index, Investor's ROR, True ROR, and Internal Rate of Return (IRR). DCFROR is the principal formal economic evaluation decision method employed by major industry to evaluate the economic potential of investments.

The method used for determining after-tax cash flows (in our leveraged situation) is simply the HAHP-ICES thermal utility's revenues less the Operating Costs (Operating & Maintenance, Insurance, Property Taxes, and Annual Energy Expense), less the Interest on Debt, less Depreciation to arrive at Taxable Income. The Taxable Income is reduced by the appropriate amount of taxes to arrive at the Net Profit, and the Depreciation is added back to arrive at the cash flow. By reducing the cash flow by the principal payment, the net cash flow is obtained. Pre-tax net cash flows differ from after-tax net cash flows simply by the appropriate amount of the tax. The analysis is provided on a pre- and after-tax basis to provide the reader with more complete information for judging the acceptability of this project. Remember, in this analysis the HAHP-ICES thermal utility has been organized as a separate corporation, whose taxable income dictates an effective tax rate. However, if this project was undertaken by an existing organization, the appropriate effective tax rate would be a function of the overall taxable income of that firm and the form of its organization, i.e., whether the firm was organized as a corporation, sole proprietorship, or partnership. In any case, the additional information is provided to accommodate these varying assumptions whose specific treatment is beyond the scope of this analysis.

The annual net cash flows and the corresponding leveraged DCFROR's are presented in Table 4.19 for the 0 through 4 turbine cases. Note that we are assuming that the annual costs for gas and electricity are escalating by 4.32% and 1.38%, respectively. A detailed sample of five years of the calculation of after-tax net cash flows is presented for inspection in Section 9.5.4.

All of the DCFROR presented in Table 4.19 are based on the situation where the individual community member's annual thermal energy charges equate the life-cycle cost of HAHP-ICES membership with that of a conventional HVAC system. If the owners of the HAHP-ICES thermal utility would accept a 15% pre-tax rate of return on their initial equity investment, the annual thermal energy charges to the community members could be reduced by the percentages that were presented in Table 4.16. Of course, if the owners of the HAHP-ICES thermal utility required a DCFROR between the 15% pre-tax minimum and the DCFROR presented in Table 4.19, lesser percentage reductions would be appropriate.

Although each of the turbine cases presented in Table 4.19 appears to offer an attractive rate of return for most potential investors, the zero turbine case (essentially an efficient conventional district space conditioning system) appears slightly more attractive (about 2% better than the one turbine case on an after-tax rate of return basis). The question of at what point the energy efficiencies of the turbine cases will offset the plant cost and maintenance advantages of the zero turbine case is brought to mind. Because the proportion of gas and electricity to the total energy consumed by the HAHP-ICES central plant varies for each of the cases, the effect of our chosen rates of energy

Table 4.19. ANNUAL NET CASH FLOWS AND EVALUATIVE CRITERIA
FOR HAHP-ICES SITE-SPECIFIC CASE

Year	0 Turbine		1 Turbine		2 Turbines		3 Turbines		4 Turbines	
	Pre-Tax NCF*	After-Tax NCF	Pre-Tax NCF	After-Tax NCF	Pre-Tax NCF	After-Tax NCF	Pre-Tax NCF	After-Tax NCF	Pre-Tax NCF	After-Tax NCF
1	112,054	103,397	110,712	103,193	104,702	99,238	101,383	97,367	96,321	93,880
2	109,702	98,925	108,832	99,413	103,107	95,606	100,183	93,960	95,469	90,893
3	107,103	94,297	106,711	94,931	101,270	92,014	98,746	90,571	94,378	87,662
4	104,245	89,769	104,340	90,574	99,182	87,689	97,063	86,907	93,045	84,471
5	101,119	85,306	101,707	86,304	96,832	83,467	95,122	82,827	91,456	80,829
6	97,713	80,845	98,801	82,086	94,208	79,312	92,912	78,832	89,603	76,950
7	94,016	76,169	95,612	77,562	91,299	75,189	90,423	74,885	87,472	73,136
8	90,014	71,557	92,127	73,112	88,094	70,974	87,643	70,956	85,053	69,351
9	85,696	66,975	88,333	68,712	84,579	66,611	84,559	66,746	82,333	65,560
10	81,047	62,395	84,218	64,332	80,741	62,280	81,158	62,563	79,300	61,482
11	66,975	51,811	70,186	54,004	66,484	51,358	66,843	51,558	64,855	50,113
12	61,623	48,065	65,387	50,644	61,959	48,191	62,768	48,705	61,153	47,522
13	55,899	44,058	60,224	47,030	57,070	44,768	58,335	45,602	57,097	44,682
14	49,784	39,778	54,682	43,151	51,799	41,079	53,527	42,237	52,670	41,583
15	43,264	34,814	48,745	38,995	46,131	37,035	48,330	38,598	47,856	38,214
16	36,321	29,259	42,396	34,082	40,050	32,170	42,726	34,276	42,640	34,172
17	28,937	23,352	35,617	28,659	33,537	26,959	36,698	29,454	37,005	29,663
18	21,093	17,042	28,390	22,878	26,574	21,389	30,229	24,278	30,931	24,805
19	12,770	10,134	20,697	16,682	19,142	15,361	23,300	18,734	24,402	19,581
20	3,947	2,811	12,517	9,893	11,221	8,787	15,889	12,631	17,396	13,852
Original Equity Investment, \$	260,061	260,061	277,464	277,464	294,534	294,534	311,033	311,033	327,864	327,864
DCFROR, ** %	40.06	34.61	37.25	32.37	32.86	28.85	30.14	26.61	27.01	24.01
Payback of Initial Equity, yrs	2.36	2.61	2.54	2.78	2.86	3.09	3.11	3.34	3.45	3.66

* Net Cash Flows, \$.

** Discounted Cash Flow Rate of Return.

escalation will vary. Table 4.20 presents the overall (or weighted average) escalation rates for each case given our assumed escalation rates (4.32% for gas, 1.38% for electricity) and the proportion of gas and electricity to the total energy consumed by the central plant (the weights). Table 4.21 displays what the weighted average energy escalation rate (WAEER) must be for each of the turbine cases to achieve a higher rate of return than the zero turbine case. For example, if the WAEER was approximately 11%, the one turbine case system would yield a higher rate of return than the zero turbine case. Given the weights for the one turbine case, an infinite number of assumed individual gas and electricity escalation rates could yield this 11% WAEER.

Table 4.20. WEIGHTED AVERAGE ENERGY ESCALATION RATES* (SITE-SPECIFIC CASE)

Number of Turbines	Weights [†]		Assumed Escalation Rates		Weighted Average Energy Escalation Rates, %
	Gas	Electricity	Gas	Electricity	
0	.69	.31	.0432	.0138	3.40
1	.71	.29	.0432	.0138	3.47
2	.74	.26	.0432	.0138	3.56
3	.75	.25	.0432	.0138	3.59
4	.77	.23	.0432	.0138	3.64

* Above general inflation.

† Proportion of the expenditure for each energy type over the total energy cost.

Table 4.21. WEIGHTED AVERAGE ENERGY ESCALATION RATES REQUIRED FOR TURBINE CASE ECONOMIC SUPERIORITY

<u>Number of Turbines</u>	<u>Required WAEER, * %</u>
1	11.1
2	12.8
3	12.8
4	13.1

* Weighted Average Energy Escalation Rate.

4.6 Summary

The HAHP-ICES concept has been shown to be viable in a number of applications (e.g., site-specific case). A community can be designed that will provide the owners of the HAHP-ICES central plant with an acceptable rate of return while simultaneously guaranteeing the community members a life-cycle cost of space conditioning that at no time exceeds that of a conventional, individually owned space conditioning system. Table 4.22 summarizes the after-tax rates of return and payback periods that were presented in Table 4.19. Although the zero turbine case, which is essentially an efficient conventional district heating system is superior to each of the turbine cases in terms of rate of return and years to payback of the initial equity, the significant fact is that each of the turbine cases provides an attractive rate of return and payback period for most investors. Any legislated tax and financial advantages based on the efficiency of energy use could only serve to make the turbine cases more attractive. It should be noted that the rates of return presented in Table 4.22 are based on the situation where the overall HAHP-ICES cost of service for community members is equivalent to that of individual conventional space conditioning system ownership. Thus, any decrease in the annual charges by the HAHP-ICES thermal utility to its community members can be thought of as a real savings in the cost of space conditioning in the conventional sense. Therefore, if the owners of the HAHP-ICES thermal utility are willing to accept a lower rate of return, they can offer these potential real savings as an inducement to attract community membership.

Table 4.22. DISCOUNTED CASH FLOW RATES OF RETURN — SITE-SPECIFIC CASE^{*}

<u>Number of Turbines</u>	<u>DCFROR, %^{**}</u>	<u>Payback of Initial Equity, yrs</u>
0	34.61	2.6
1	32.37	2.8
2	28.85	3.1
3	26.61	3.3
4	24.01	3.7

* Based on after-tax net cash flows.

** Discounted cash flow rate of return. The HAHP-ICES cost of service for community members is set equal to that of individual conventional space conditioning system ownership.

Note: The cost of the thermal distribution system and its associated losses has been incorporated into this analysis.

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5. EXPECTED ENVIRONMENTAL IMPACTS

In general, for the factors examined (air emissions, solid wastes, noise, thermal discharges, land utilization, aesthetics, and safety), HAHP-ICES is either less desirable or equal to the conventional system from an "onsite" frame of reference. However, when examined in terms of an "at source" frame of reference, the heat-pump-based system is clearly better in terms of air emissions, thermal discharges, and solid wastes. Aesthetics, noise, and safety will not be significantly different between the heat-pump-based system and the conventional system.

In comparing the HAHP-ICES with electrically powered conventional equipment in terms of emissions and source of energy, a composite utility was assembled. This composite utility consisted of four existing electrical utilities combined to form a single utility having a composite generation mix with an associated heat rate. The utilities were selected as representative of Northeast utilities with average heat rates that were intermediate (that is, some utilities had better rates, some worse). The utilities were also selected to have a large percentage of their generation mix supplied by fossil fuels (i.e., low nuclear capacity). The four utilities which were combined were Pennsylvania Power and Light, Public Service of Indiana, Niagara Mohawk Power Corp., and Detroit Edison. The generation mix and heat rate that resulted were:

Coal	77%
Oil	18%
Gas	2%
Nuclear	3%
Heat Rate	10,284 Btu/kWh

A utility operating with an average heat rate of 10,284 Btu/kWh would be ranked number 20 of the top 100 utilities in the United States in terms of 1977 operating performance. Assuming a 10% energy loss in transmission and distribution to the end-use point, the heat rate on a delivered kWh basis is 11,500 Btu/kWh.

5.1 Discharges

5.1.1 Air

The calculated air emissions on a delivered kWh basis were calculated using average emission factors compiled by the EPA for each fuel in the generation mix or the EPA-specified limits for air pollution, whichever was less. The results were the following:

Particulates	1.003×10^{-3}	lb/kWh delivered
SO ₂	1.227×10^{-2}	lb/kWh delivered
CO	4.149×10^{-4}	lb/kWh delivered
Hydrocarbons	1.383×10^{-4}	lb/kWh delivered
NO _x	7.47×10^{-3}	lb/kWh delivered

Air pollutants emission factors for the gas-fired HAHP and gas-fired domestic and commercial heating equipment are shown in Table 5.1. They represent average values compiled by the EPA for residential and commercial gas-fired equipment.² Table 5.2 shows the approximate air emissions that result from the heat-pump system and conventional equipment when providing 1×10^6 Btu of heat and 1×10^6 Btu of refrigeration.

Table 5.1. AIR POLLUTANT EMISSION FACTORS FOR GAS-FIRED EQUIPMENT

Pollutant	Residential Heating Units	Commercial Heating Units*
	lb/ 10^6 Btu input	
Particulates	1.81×10^{-2}	1.81×10^{-2}
SO ₂	5.71×10^{-4}	5.71×10^{-4}
CO	1.90×10^{-2}	1.90×10^{-2}
Hydrocarbons	7.62×10^{-3}	7.62×10^{-3}
NO _x	7.62×10^{-2}	1.14×10^{-1}

* These values used for HAHP-ICES gas-fired boiler.

5.1.2 Water

A major effluent from both the HAHP-ICES and the conventional system is blowdown from the boiler and cooling water systems. It will be concentrated in salts, such as calcium carbonate, and other impurities. It should be disposable by discharge to a community sewer or storm drainage system without pretreatment. It should be noted that no new water pollutants are generated and the concentrated salts of the blowdown are re-diluted when they are discharged.

5.1.3 Solid

Dust collected on filters and by other devices is a solid waste generated by the HAHP-ICES and the conventional system. It is produced in small amounts and can be amassed with the community trash and disposed of in sanitary landfills. Worn and broken parts are another source of solid wastes. They may be salvaged and remanufactured or sent to a landfill.

5.1.4 Thermal

5.1.4.1 Base Case

Waste heat is released to the environment through cooling towers and flues for both the HAHP-ICES and conventional systems. Under conditions of low temperature and high relative humidity, fogging will occur in the discharge area of the cooling tower. This could cause aesthetic complaints and safety problems for motorists if fogging spreads to roadways. Judicious placement of cooling

Table 5.2. AIR POLLUTION EMISSIONS FROM VARIOUS HEATING AND COOLING SYSTEMS
PRODUCING 1×10^6 BTU/HR OUTPUT ON A SOURCE ENERGY BASIS

HAHP-ICES CENTRAL PLANT				
COP*	Internal Heat Source (Ambient Temperature 30°F)	External Heat Source (Ambient Temperature 30°F)	Cooling (Ambient Temperature 90°F)	
At Site	1.21	1.02	0.88	
At Source	1.15	0.97	0.84	
Pollutants, lb/hr				
Particulates	1.56×10^{-2}	1.85×10^{-2}	2.15×10^{-2}	
SO ₂	4.94×10^{-4}	5.83×10^{-4}	6.80×10^{-4}	
CO ₂	1.64×10^{-2}	1.94×10^{-2}	2.26×10^{-2}	
Hydrocarbons	6.58×10^{-3}	7.77×10^{-3}	9.07×10^{-3}	
NO _x	9.85×10^{-2}	1.17×10^{-1}	1.35×10^{-1}	
Conventional Equipment				
COP*	Gas-Fired Residen- tial Furnace	Gas-Fired Commercial Boiler	Electric Heating	Electric Air Conditioner
At Site	0.70	0.83	1.00	3.74
At Source	0.67	0.79	0.297	1.11
Pollutants, lb/hr				
Particulates	2.70×10^{-2}	2.29×10^{-2}	2.93×10^{-1}	7.86×10^{-2}
SO ₂	8.52×10^{-4}	7.23×10^{-4}	3.59	9.61×10^{-1}
CO ₂	2.84×10^{-2}	2.41×10^{-2}	1.22×10^{-1}	3.25×10^{-2}
Hydrocarbons	1.14×10^{-2}	9.65×10^{-3}	4.05×10^{-2}	1.08×10^{-2}
NO _x	1.14×10^{-1}	1.44×10^{-1}	2.19	5.85×10^{-1}

* Gas-based source emissions and COP's assume 5% transmission losses, with these losses having the same pollutant mix as the site consumed gas.

Electricity based source emissions and COP's assume a 29.68% electrical generating, transmission and distribution efficiency.

towers circumvents these problems. Both systems discharge about 5 billion Btu of waste heat at the site per year.

5.1.4.2 Site-Specific Case

For the site-specific community of one office building, one retail building, five high-rise buildings, five low-rise buildings and 42 townhouses, thermal discharges have been approximated for conventional equipment and the HAHP-ICES using 0 and 4 turbines. Thermal discharge is defined as the waste heat emanating from cooling towers and stack flues. The estimates presented below are based on the average COP of the various pieces of heating and cooling equipment and are subject to minor inaccuracies.

5.1.4.2.1 Conventional HVAC Equipment

Total thermal discharges are about 23 billion Btu per year; 14 billion result from flue losses and 9 billion are from cooling tower discharges.

5.1.4.2.2 HAHP-ICES

Total thermal discharges are about 18 billion Btu per year for both the 0- and 4-turbine case. Discharges are expected to also be 18 billion Btu per year for the 1-, 2-, and 3-turbine cases.

5.2 Failure Mode

Serious types of failures considered for the HAHP-ICES are hot-water leaks from the distribution piping and a sudden release of refrigerant from the HAHP central plant.

A major cause of distribution piping leaks is corrosion, which can be controlled by conditioning of the water. Chemicals are used to reduce hardness and maintain water at an alkaline pH that prevents corrosion.³ Sodium sulfite in dilute concentration is a typical chemical added to the distribution system. Sodium sulfite exhibits low toxicity, i.e., chronic human exposure causes biological changes that readily reverse at the end of the exposure.⁴ If a leak develops in the HAHP-ICES distribution piping to the residences, inconsequential amounts of chemicals would be released to the soil. Similarly, a leak from piping within buildings should not be hazardous to the occupants because the chemicals that are present in the water exhibit low toxicity, would only be present at dilute concentrations, and would be unlikely to disperse because of their low volatility. The chemicals would be contained at the site of the leak and could easily be cleaned up. Hot-water leaks could also cause scalds to occupants; the impact of hot-water leaks in occupied spaces for the HAHP-ICES would be equivalent to that of conventional baseboard heating.

The refrigerant employed in the HAHP-ICES is a halogenated hydrocarbon (e.g., Freon[®]) and is subject to accidental release. The inventory for both the HAHP-ICES and the conventional system is approximately equal. Freon-22 (chlorodifluoromethane) is non-flammable and exhibits toxicity principally by

acting as an asphyxiant; it begins to be hazardous at concentrations of about 14% in air by volume. When heated to a high temperature in the presence of air, toxic chloride fumes, such as phosgene, can be generated.⁴ If the refrigerant leaks within the HAHP-ICES, the hazard would be confined to the equipment building; the same is true for the conventional system. Because equal amounts of refrigerant are present in both systems, it is expected that a refrigerant release from either system would have approximately equal environmental impacts.

5.3 Decommissioning Impacts

Although the HAHP-ICES is composed of different types of components than the conventional system, the aggregate amount, or weight of equipment, is equal on an order-of-magnitude basis. As equipment reaches the end of its useful life, it is dismantled and removed and scrapped or salvaged. If required, the refrigerant can be collected to prevent release to the atmosphere. The impacts from decommissioning the HAHP-ICES are expected to be equivalent to those of a conventional system.

5.4 Resource Consumption

5.4.1 Construction

Resources are consumed during construction of the HAHP-ICES and the conventional system. Power is required to operate machines for digging trenches, transporting equipment, lifting objects, and to support general construction activities. Most of the power is expected to be generated by petroleum-based fuels, such as motor gasoline and diesel fuel. Materials such as steel, concrete, and plastics, are consumed in construction of both systems.

5.4.2 Operation

The major resource consumed by the HAHP-ICES is natural gas, with small amounts of electricity required for fans, pumps, and use of backup equipment. The baseline system using conventional heating and cooling equipment consumes more gas and more electricity.

5.5 Land Utilization

For the HAHP-ICES, areas are required for the central plant, distribution lines, outside heat recovery unit, and the cooling tower. For the conventional system, space is required for the boiler, air-conditioning unit, water storage tank, and cooling tower.

5.6 Annual Emissions Comparison

5.6.1 Base Case

For the one office, five residential building base-case community, the annual emissions were calculated for both the HAHP-ICES and the conventional system. In the case of the HAHP-ICES, emissions were calculated based on the gas consumed plus the emissions resulting from the electricity consumed by the system. For the conventional system, the emissions resulting from the electric

consumption of the office building were combined with the emissions resulting from the gas consumption in the residential units. The net result was that the HAHP-ICES results in reduced emissions of 55.9 to 3937 lb/yr, depending upon the pollutant. Table 5.3 shows the emissions for the heat-pump and conventional case.

5.6.2 Site-Specific Case

For the site-specific community of one office building, one retail building, five high-rise buildings, five low-rise buildings and 42 townhouses, annual emissions were calculated for the conventional system and the HAHP-ICES for the cases of 0, 1, 2, 3, and 4 turbines. Emission estimates were based on total gas and total electricity consumption for each system. The greatest reduction in emissions occurred for the HAHP-ICES using 4 turbines; annual emissions were reduced 180 to 14,100 pounds, depending upon the pollutant. Net reductions are shown in Table 5.4.

5.7 Annual Resource Comparison

Table 5.5 summarizes the operating resources consumed and space requirements for heating and cooling equipment for both the HAHP-ICES and conventional systems.

Table 5.5: ANNUAL OPERATING RESOURCES AND LAND UTILIZATION

	<u>Natural Gas (SCF)</u>	<u>Electricity (kWh)</u>	<u>Equipment Building Space (ft²)</u>
Base Case			
Conventional	10.5 X 10 ⁶	414,600	1000
HAHP-ICES	9.4 X 10 ⁶	93,800	1000
Site-Specific			
Conventional	58 X 10 ⁶	1,413,000	2000
HAHP-ICES			
0 turbine	57 X 10 ⁶	907,000	2000
1 turbine	56 X 10 ⁶	577,000	2000
2 turbines	56 X 10 ⁶	435,000	3000
3 turbines	55 X 10 ⁶	337,000	3000
4 turbines	55 X 10 ⁶	264,000	3000

Table 5.3. ANNUAL EMISSION FROM HAHP-ICES AND CONVENTIONAL SYSTEMS SERVING A COMMUNITY OF ONE OFFICE BUILDING AND FIVE 24-UNIT RESIDENTIAL BUILDINGS ON A SOURCE BASIS*

HAHP-ICES			
Pollutants, lb/yr	From 9481.10 X 10 ³ ft ³ of Gas Consumed	From 93,793.5 kWh of Electricity Consumed	Total
Particulates	175.1	94.1	269.2
SO ₂	5.6	1150.9	1156.5
CO ²	183.8	38.9	222.7
Hydrocarbons	73.7	13.0	86.7
NO _x	1102.4	700.6	1803.0

Baseline System/Conventional Equipment**			
Pollutants, lb/yr	From 10,447.56 X 10 ³ ft ³ of Gas Consumed	From 414,620 kWh of Electricity Consumed	Total
Particulates	202.5	415.9	618.4
SO ₂	6.4	5087.4	5093.8
CO ²	212.6	172.0	384.6
Hydrocarbons	85.3	57.3	142.6
NO _x	852.6	3097.2	3949.8

Net Reduction for HAHP-ICES		
Pollutants	lb/yr	%
Particulates	349.2	56.4
SO ₂	3937.3	77.3
CO ²	161.9	42.1
Hydrocarbons	55.9	39.2
NO _x	2146.8	54.3

* Assumes 5% gas transmission losses and electrical production and transmission efficiency of 29.68%. Values include thermal losses and energy required for pumping.

** Baseline electricity and gas are the amounts displaced by the HAHP-ICES.

Table 5.4. NET EMISSION REDUCTION FOR HAHP-ICES SITE-SPECIFIC CASE

<u>Number of Turbines</u>	<u>Pollutant</u>	<u>lb/yr</u>	<u>%</u>
0	Particulates	516.1	20.9
	SO ₂	6,207.3	35.8
	CO	218.9	12.9
	Hydrocarbons	73.6	11.5
	NO _x	3,249.5	19.6
1	Particulates	871.2	35.3
	SO ₂	10,277.1	59.2
	CO	831.4	22.6
	Hydrocarbons	129.5	20.4
	NO _x	5,865.5	35.4
2	Particulates	1,006.6	40.8
	SO ₂	12,000.4	69.1
	CO	432.7	25.6
	Hydrocarbons	146.1	22.9
	NO _x	6,882.6	41.4
3	Particulates	1,120.4	45.4
	SO ₂	13,193.4	76.0
	CO	490.2	29.0
	Hydrocarbons	166.3	26.1
	NO _x	7,711.8	46.5
4	Particulates	1,201.7	48.7
	SO ₂	14,100.4	81.2
	CO	528.4	31.3
	Hydrocarbons	179.6	28.2
	NO _x	8,309.1	50.1

5.8 Summary

The environmental impacts of the base-case HAHP-ICES and the conventional system are summarized below.

- Total air emissions are 40% to 60% less for the HAHP-ICES.
- Water effluents are approximately equal and have negligible impacts.
- Solid discharges at the site for both systems are negligible.
- Thermal discharges (waste heat) at the sites of both systems are about 5 billion Btu/yr.
- System failures are expected to have nearly equivalent impacts.
- Decommissioning impacts are expected to be the same.
- The conventional system consumes 15% more gas and four times as much electricity during operation.
- Both systems' central plants require about 1000 square feet of space.

The impacts that differ for the site-specific case are summarized as follows:

- Total air emissions are reduced 15% to 80% by the HAHP-ICES depending on the pollutant and the number of turbines in the HAHP-ICES.
- Thermal discharges for the HAHP-ICES are about 20% less than those from the conventional system.
- The conventional system consumes about 7% more gas and three times more electricity than the HAHP-ICES.
- The HAHP-ICES generally requires a larger equipment building.

5.9 References Cited

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6. COMMUNITY GROWTH

6.1 Introduction

In much the same way as a conventional communities' growth pattern would be of interest to the local electric power and gas utilities, an ICES communities' growth directly influences the design of the HAHP central plant. The effect of growth in an ICES system, however, should be several orders of magnitude greater on the central plant, based on the differing sizes or capacities for the "utilities". For example, adding one building in a conventional community would have a small effect on the local gas company, while in an ICES community, the economics and performance of the entire system may be significantly changed.

In the following discussions on community growth, the emphasis is on the preferred expansion of the community with respect to the central plant's performance and the ICES economic viability. These preferred growth patterns are not difficult to envision and, therefore, would seem likely to gain acceptance from both the developer and existing occupants of the community.

6.2 Base Case Application

The configuration and design of the HAHP-ICES central plant discussed as the base case application is centered, to a large extent, upon the loads presented to the plant by the community. These are as follows:

1. The office building size was selected to allow full use, by the central plant, of the wintertime internal cooling load.
2. The central plant's cooling capacity was sized to meet the summertime cooling requirements of the office building.
3. Wintertime base-loading of the central plant's turbine/heat pump-derived heat was ensured by "adding" apartment buildings to the community until the average heating demand of the entire community equaled the heat available at the turbine/heat pump condensers.

As a result of assembling the base case by this method, the office building becomes the key component in the building mix. In other words, the overall HAHP-ICES system presented in this application cannot grow in turbine/heat pump capacity until another office building is built. Moreover, it is unlikely that the community would always grow in ratios of five apartment buildings to one office building. What is probable, however, is a growth pattern that has residential and office buildings being added to the community such that this ratio changes with time. The question therefore, is what is the effect on the central plant's performance and economics with an expanded community which has, for example, ten apartment buildings and one office building, or five apartment buildings and two office buildings?

Increases in the number of apartment buildings only will require the addition of greater auxiliary boiler capacity; conversely, increases in the number of office buildings will require the addition of another steam generator/turbine/heat pump unit. The effect on the performance of the central plant by community growth in these opposing directions is shown in Figure 6.1. The values given along the left ordinate are the heating COP's for the entire system, during the months of January through March. The building loads and central plant performance factors are identical to those discussed in Section 3. The right ordinate is the annual primary energy savings of the HAHP-ICES over that of the conventional HVAC equipment, also discussed in Section 3. Adding an office building to the community, in essence, results in a community mix of 2.5 apartment buildings to one office building. The effect of this type of growth is very slight on the heating COP. What is likely to occur is that during the heating season, the heat pump's condenser is being fully utilized as a source of heat for the community. Nevertheless, the penalty associated with this type of growth is illustrated in the curve of annual primary energy savings, which falls by almost five points. This decrease is a result of the community's decrease in net domestic hot-water demand per turbine installed in the central plant, which during the summer is the principal thermal load for heat contained in the exhaust of the turbine driving the heat pump. As will be shown later, this decrease has a crucial impact on the system's economics.

If residential buildings are added to the community, both the heating COP and annual primary energy savings will decrease. The decrease in heating COP values is associated with the plant's increasing auxiliary boiler (COP = 0.83) capacity required to meet the increased heating season demand.

More important, however, is the gradual fall in energy savings values, again the result of the effect of domestic hot-water demands of the community. During the summer months, when the turbine is utilized to drive the heat pump in a cooling mode, the turbine exhaust heat may be fully utilized for the DHW demand. This is illustrated in Figure 6.2, which shows the annual heat rejected to the cooling towers. In addition, it should be noted that during the winter months almost no heat is rejected or wasted. As the number of residential buildings is increased, the amount of reject heat falls dramatically and then starts to level off, signifying probable full utilization of this heat.

From an economic viewpoint, the most appropriate direction for the community to expand is one that increases the number of apartment buildings, as shown in Figure 6.3. The values shown are the present values of the excess capital generated by the ICES system. As the number of residential buildings is increased by one, the capital generated increases by just over \$25,000. The reason lies in the fact that increasing the auxiliary boiler capacity is relatively inexpensive, while the revenues gained from these additional buildings are quite significant.

Using the values for the thermal distribution system cost of \$45,000 for five apartment buildings (Section 4), when the community has expanded to the size of 15 apartment buildings and one office building, the system could economically justify the expense of building another HAHP-ICES central plant in an associated office building. Perhaps not coincidentally, this would place the overall system near the peak values for heating COP and energy savings shown in Figure 6.1, with an office to residential building ratio of about seven and one-half to one.

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Figure 6.1. EFFECT OF BASE CASE COMMUNITY GROWTH ON HEATING COP AND ENERGY SAVINGS

Figure 6.2. EFFECT OF BASE CASE COMMUNITY GROWTH ON ANNUAL HEAT REJECTED TO COOLING TOWERS

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Figure 6.3. EFFECT OF BASE CASE COMMUNITY GROWTH ON SYSTEM SURPLUS GENERATED BY HAHP-ICES

6.3 Site-Specific Case

In contrast to the base case application of the HAHP-ICES, a community of the size of the Monroeville complex allows a more detailed analysis of how the community might be constructed. In other words, having a priori knowledge of the proposed communities' final configuration, in what order should the buildings be constructed so as to maximize the central plants' performance and minimize the cost of delivered energy to the existing community occupants?

In the following discussion of the Monroeville complex's expansion, several assumptions have been made. They are:

1. That the number of turbine/heat pump units contained in the final central plant is known before the construction work begins. Thus, the decision on cost savings (less turbines) versus energy savings (more turbines) has been made.
2. That the thermal distribution network is sized to handle the entire communities' loads. Thus, a particular segment will be oversized (and costly) until the entire community is presented as a load, at which time the segment is at the design point.
3. That the operating personnel of the central plant increase as the community expands.
4. That the entire complement of buildings within the Monroeville complex are built. If this is not the case, it is known before construction begins.

The expansion of the central plant's capacity is tied not only to the number of turbine/heat pump units, but to the size of the peaking units. It should be remembered that in the final central plant designs, there are two peak chillers and two peak auxiliary boilers. Therefore, as the community expands, the number of turbine/heat pump units may or may not increase because it may prove more economic to add another peaking unit immediately, then add a turbine/heat pump unit at the next increment of growth. As will be shown, this choice of a very efficient, but costly turbine/heat pump versus the inexpensive conventional peaking unit is principally an economic one.

The kernel, or starting point for the community is the office and retail (shopping center) buildings. The complex then expands as high-rises, low-rises, and then townhouses are added. Tables 6.1 through 6.4 detail the expansion of the central plant as the community expands. Each central plant's design is based on the final number of turbine/heat pump units to be installed, since the required capacity of the peaking units is fixed by these base-loaded units. As may be noted in these tables, the major electrically-driven chiller is brought on-stream early in the expansion, while the smaller chiller is installed only after the entire high-rise sector is built; the same is true for the auxiliary boilers. Special note should be taken of the central plant with a final design of four turbine/heat pump units. Both peak chillers are installed at the beginning, but the majority of turbines are installed after all the high-rises are built.

Table 6.1. EXPANSION OF HAHP CENTRAL PLANT WITH PHASED COMMUNITY GROWTH
(One Turbine/Heat Pump Unit to be Employed in Final Plant Configuration)

<u>Phase In Community Growth</u>	<u>Buildings Contained</u>	<u>Total Number of Turbine/Heat Pump Units Installed</u>	<u>Installed Capacity of Peaking Units</u> <u>10⁶ Btu/hr</u>			
			<u>Chiller #1</u>	<u>Chiller #2</u>	<u>Auxiliary Boiler #1</u>	<u>Auxiliary Boiler #2</u>
1	Office/Retail	0	7.42	0	13.5	0
2	Office/Retail Two High-Rise	1	7.42	0	13.5	0
3	Office/Retail Five High-Rise	1	7.42	2.06	13.5	4.25
4	Office/Retail Five High-Rise Five Low-Rise	1	7.42	2.06	13.5	4.25
5	Office/Retail Five High-Rise Five Low-Rise 42 Townhouses	1	7.42	2.06	13.5	4.25

Table 6.2. EXPANSION OF HAHP CENTRAL PLANT WITH PHASED COMMUNITY GROWTH
(Two Turbine/Heat Pump Units to be Employed in Final Plant Configuration)

Phase In Community Growth	Buildings Contained	Total Number of Turbine/Heat Pump Units Installed	Installed Capacity of Peaking Units			
			10 ⁶ Btu/hr			
			Chiller #1	Chiller #2	Auxiliary Boiler #1	Auxiliary Boiler #2
1	Office/Retail	0	6.81	0	12.37	0
2	Office/Retail Two High-Rise	1	6.81	0	12.37	0
3	Office/Retail Five High-Rise	2	6.81	1.85	12.37	3.87
4	Office/Retail Five High-Rise Five Low-Rise	2	6.81	1.85	12.37	3.87
5	Office/Retail Five High-Rise Five Low-Rise 42 Townhouses	2	6.81	1.85	12.37	3.87

Table 6.3. EXPANSION OF HAHF CENTRAL PLANT WITH PHASED COMMUNITY GROWTH
(Three Turbine/Heat Pump Units to be Employed in Final Plant Configuration)

Phase In Community Growth	Buildings Contained	Total Number of Turbine/Heat Pump Units Installed	Installed Capacity of Peaking Units			
			10 ⁶ Btu/hr		Auxiliary Boiler #1	Auxiliary Boiler #2
			Chiller #1	Chiller #2		
1	Office/Retail	0	6.2	0	11.0	0
2	Office/Retail Two High-Rise	1	6.2	0	11.0	0
3	Office/Retail Five High-Rise	3	6.2	1.65	11.0	3.5
4	Office/Retail Five High-Rise Five Low-Rise	3	6.2	1.65	11.0	3.5
5	Office/Retail Five High-Rise Five Low-Rise 42 Townhouses	3	6.2	1.65	11.0	3.5

Table 6.4. EXPANSION OF HAHP CENTRAL PLANT WITH PHASED COMMUNITY GROWTH
(Four Turbine/Heat Pump Units to be Employed in Final Plant Configuration)

Phase In Community Growth	Buildings Contained	Total Number of Turbine/Heat Pump Units Installed	Installed Capacity of Peaking Units			
			10 ⁶ Btu/hr		Auxiliary Boiler #1	Auxiliary Boiler #2
			Chiller #1	Chiller #2		
1	Office/Retail	0	5.6	1.44	9.88	0
2	Office/Retail Two High-Rise	1	5.6	1.44	9.88	0
3	Office/Retail Five High-Rise	4	5.6	1.44	9.88	3.13
4	Office/Retail Five High-Rise Five Low-Rise	4	5.6	1.44	9.88	3.13
5	Office/Retail Five High-Rise Five Low-Rise 42 Townhouses	4	5.6	1.44	9.88	3.13

The peculiar jump in number of turbine/heat pump units which occurs in Tables 6.1 through 6.4 results from the economics of central plant cost versus the thermal distribution network cost. This trade-off is shown in Table 6.5, which also demonstrates the effect of the sizing of the thermal distribution network to handle the final completed community's requirements (see Assumption No. 2). The negative economic balance shown in Table 6.5 for the growth phase 1 results from the costly (\$89,000) installation of transmission mains to the office and retail buildings from the central plant which, at this stage, is not central at all as shown in Figure 1.17. The addition of two high-rise buildings requires that transmission mains be installed from the central plant to the general area of the residential buildings in the community. In other words, the core of the transmission network would be required to be in place, yet its cost of \$93,000 would be distributed among too few loads. As the remaining high-rises are added (additional network cost = \$87,000), the economic balance shifts to positive values, excluding the four turbine/heat pump case. The cost of the four turbine/heat pumps for the central plant is too great to be offset by the cost savings associated with the community in growth phase 3. At such time as when the low-rise apartment buildings are added to the community, the positive economic balance is established for all four central plant variants. The cost of adding to the distribution network for these low rises is only \$31,000.

Table 6.5. ECONOMIC BALANCE OF HAHP CENTRAL PLANT EXPANSION
WITH PHASED COMMUNITY GROWTH

<u>Phase In Community Growth</u>	<u>Buildings Contained</u>	<u>Total Number of Turbine/Heat Pump Units Installed</u>	<u>Economic* Balance, \$</u>
1	Office/Retail	0	- 22,000
2	Office/Retail		
	Two High-Rise	1	- 74,000
		2	- 123,000
3	Office/Retail		
	Five High-Rise	1	+ 91,000
		2	+ 47,000
		3	+ 11,000
		4	- 36,000
4	Office/Retail		
	Five High-Rise		
	Five Low-Rise	1	+ 167,000
		2	+ 110,000
		3	+ 91,000
		4	+ 48,000
5	Office/Retail		
	Five High-Rise		
	Five Low-Rise		
	42 Townhouses		

See Section 4, Economics

* Balance of present value of future net revenues versus system cost including thermal distribution network.

In summary, it is the cost of the thermal distribution network during the early stages of growth for the community which form a constraint on that growth. If the entire complement of buildings is planned, but not completed, the economics viability of the community may or may not be in jeopardy, depending on which buildings are actually built. For example, if only the office and retail buildings are completed, the concept's implementation is not economically justified if the system was designed as if the entire community were to be built. On the other hand, if the community was prevented from expanding after the high rises were added, the in-place residents of the complex should not suffer any economic penalties associated with their thermal demands caused by this lack of completion. While the same may be said of conventional HVAC equipment, this is an important consideration for integrated energy systems where the final design is based on a proposed community.

7. IDENTIFIED VARIATIONS

The variations on the base HAHP-ICES concept that are identified in this section permit operation of the concept in different modes and tailor its output to community requirements. The benefits of a variation in the system concept may be considered in two contexts: First, from the thermal utility's viewpoint, the proposed variation should provide the following benefits in the form of reduced system complexity:

- Reduction in the multiplicity of system components
- Reduction in the complexity of system controls, thus providing an increased ease of operation of the system with less room for operator error and a greater probability of operating in the most efficient mode
- Increase in reliability, with the potential for a reduction in operating and maintenance costs.

Variations must also be considered from the customer's viewpoint: A variation is a benefit if it makes the system more convenient to use and/or it results in a lower utility bill. The impact of a variation on the customer's utility bills is the primary determinant of the benefit of the variation. A variation is also a benefit if it increases the potential market for the HAHP-ICES concept.

The identified variations include the following:

- Alternative fuels
- Alternative prime movers
- Electric power production
- Alternative heat sources
- Multiple compressors
- Multiple heat pump evaporators
- Thermal energy storage.

Whether such variations are promising, however, requires a detailed engineering assessment of the impacts of these variations on operation of the thermal utility, impacts on the system performance, and the resultant implications for system economics as perceived by the customer.

7.1 Alternative Fuels

The use of natural gas as the primary fuel to the HAHP-ICES has been assumed throughout the preceding sections. The purpose of this section is to explore the effects of using alternative gaseous, liquid, and solid fuels.

7.1.1 Baseload Usage of Alternative Gaseous or Liquid Fuels

Alternatives to the baseline Rankine Steam System, now under development under DOE Contract No. EY-76-C-02-2883, are addressed in this subsection. It is expected that alternative prime movers may represent a more favorable fit to many specific community site requirements.

Conventional boiler equipment is currently available in the size ranges needed for HAHP-ICES that can utilize natural gas, high- or medium-Btu gases, and distillate oils. The cost of these fuels (along with the cost of other forms of energy) is presented in Figure 7.1, in terms of dollars/million Btu. As can be seen in this figure, the cost range for gaseous and liquid fuels varies by a factor of more than 4:1. For all conventional (currently marketed) fuels, the costs reflect the current (late 1978 dollars) city-gate price. The cost of fuels that are dependent upon advanced technologies has been calculated from published design literature and brought to late 1978 dollars through the use of inflation indices.

Generally, most boilers that consume a gaseous or liquid fuel are similar in design except for burners and fuel supply systems. For this reason, the cost of a medium- or high-Btu gas-fired boiler or a liquid fuel-fired boiler is nearly the same. However, the total system cost is affected by the need for a liquid storage system when firing distillate oils, kerosene, or LPG. The cost factor associated with boiler/storage systems operating on various types of fuel is shown in Table 7.2. These costs reflect the difference in boiler costs as well as in fuel storage and handling cost. The natural-gas-fired system — the base case — has an equipment cost factor assigned as unity (1.0). The cost adjustment factor applies only to the capital cost of the steam-generating component of HAHP-ICES. The cost of the equipment required to utilize alternative fuels corresponds to a steam output of about 1.5×10^6 Btu/hr. The cost adjustment factor for systems with larger steam outputs, particularly coal-fired systems, will be smaller because the magnitude of the fuel-handling equipment cost will be a smaller fraction of the overall steam-generating system cost. The applicability of a given fuel to a boiler system, and the current equipment availability for each fuel, are also presented in Table 7.2. A summary evaluation of the most feasible alternative gaseous and liquid fuels is presented in Table 7.3. The economic analyses presented in this table are centered upon the base case. It is expected that the general trends and conclusions which may be drawn from these analyses would be equally applicable to the site-specific case; the central plant for the Monroeville complex will contain one or more steam generators of an equal size compared to that of the base case.

7.1.2 Baseload Usage of Selected Solid Fuels

Solid fuels are available in many forms. The evaluation herein, however, will be limited to coal and urban solid waste material. These fuels are more widely available than others, which include wood, wood waste, peat, etc.

* See Table 7.1 for fuel type corresponding to each number.

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Figure 7.1. CITY GATE COST OF VARIOUS FUELS (Late 1978 Dollars)

Table 7.1. LEGEND FOR FIGURE 7.1

Fuel Type

1. Raw Coal (not cleaned or sized; needs further processing for boiler use).
2. Low-Btu Gas (150 Btu/SCF). From coal gasification.
3. High-Btu gas (~1000 Btu/SCF). From coal gasification.
 - A. Second Generation Technology
 - B. Commercial Lurgi
4. Syn Crude from Coal (needs further processing for boiler use).
5. Syn Crude from Shale (needs further processing for boiler use).
 - A. Modified in situ
 - B. Surface Retorting
6. No. 1 Distillate (134,950 Btu/gal - 6.81 lbs/gal) Chicago.
7. No. 2 Distillate (139,400 Btu/gal - 7.03 lbs/gal) Chicago.
8. No. 5 Distillate 1%S max Chicago (148,400 Btu/gal - 7.81 lbs/gal).
9. No. 6 Distillate 1%S max Chicago (153,600 Btu/gal - 8.25 lbs/gal).
10. Kerosene 42-43 Cetane (135,600 Btu/gal - 6.75 lbs/gal).
11. Electricity (3.25¢/kWhr).
12. Steam Coal <1%S; 25×10^6 Btu/ton; cleaned and sized for stoker boiler use.
13. Steam Coal >3%S; 25×10^6 Btu/ton; cleaned and sized for stoker boiler use.
14. Propane 91,065 Btu/gal.
15. n-Butane 102,989 Btu/gal.
16. Natural Gas (1000 Btu/SCF)
 - A. Current price
 - B. Price increase due to deregulation.
17. Imported LNG (1000 Btu/SCF).
18. Coal-Derived Steam (steam purchased directly from producer).
19. SNG from biomass using manure.
20. Hydrogen from Ocean Thermal Energy Conversion facility.
21. SNG from Ocean Thermal Energy Conversion facility.
22. Average Crude Oil price.
23. No. 2 Distillate produced from coal-derived Syn Crude.

Table 7.2, Part 1. EFFECT OF ALTERNATIVE FUEL ON SYSTEMS CAPITAL COSTS

<u>Type of Fuel</u>	<u>Cost Adjustment Factor*</u>	<u>Equipment Availability</u>
Raw Coal ^a	N.A. ^{**}	N.A.
Low-Btu Gas (from coal) ^b	1.2 [†]	C.N.A. [†]
High-Btu Gas (from coal)	1.0	Commercial ^g
Syn Crude (from coal) ^c	N.A.	N.A.
Syn Crude (from shale) ^c	N.A.	N.A.
No. 1 Distillate ^d	1.43	Commercial
No. 2 Distillate ^d	1.43	Commercial
No. 5 Distillate (1% S max) ^d	1.50	Commercial
No. 6 Distillate (1% S max) ^d	1.50	Commercial
Kerosene ^d	1.43	Commercial
Electricity	1.12	Commercial
Cleaned and Sized Coal (<1% S) ^{d,e,f}	6.0	C.N.A.
Cleaned and Sized Coal (>3% S) ^{d,e,f}	7.0	C.N.A.
Cleaned and Sized Coal (>3% S) for Fluidized-Bed Combustion	5.75	C.N.A. ^{***}
Propane ^d	1.45	Commercial
n-Butane ^d	1.45	Commercial
Natural Gas	1.0	Commercial
Imported LNG ^g	1.0	Commercial ^g
Coal-Derived Steam	N.A.	N.A.
SNG From Biomass ^g (manure)	1.0	Commercial ^g
Hydrogen From OTEC ^h	C.N.A.	C.N.A.
SNG From OTEC ^g	1.0	Commercial ^g
Crude Oil ^c	N.A.	N.A.
Solid Waste	<1.0	C.N.A.

Table 7.2, Part 2. EFFECT OF ALTERNATIVE FUEL ON SYSTEMS CAPITAL COSTS

- * Based on 1.0 being the capital cost of a natural gas-fired system. The cost adjustment factor applies only to the capital cost of the steam-generating equipment compared to the cost of the natural-gas-fired steam boiler used in the HAHP-ICES concept.
- ** N.A. = Not applicable.
- † C.N.A. = Commercially not available in size range studied.
- *** Fluidized-bed boilers are commercially not available for high-temperature and pressure steam production. The cost adjustment factor shown is for a unit producing steam at 150 psig.
- a Raw coal as taken from the mine must be cleaned and sized before it can be used for boiler application.
- b Low-Btu gas may not generate a high enough heat release rate to produce a steam of high temperature and pressure.
- c Crude oil requires further processing for boiler application.
- d One week of storage included in Cost Adjustment Factor.
- e Coal is cleaned and sized for stoker application.
- f These costs have been extrapolated from the closest commercially available size.
- g SNG produced from these sources is identical to natural gas and, therefore, utilizes the same boiler equipment.
- h Hydrogen burners for boiler application are currently in the developmental stage.

Table 7.3. SUMMARY EVALUATION OF FEASIBLE ALTERNATIVE FUELS FOR HAHP-ICES
(Base Case Community)

Alternative Fuels	Availability of Necessary Equipment		Economics Compared To Natural Gas		Estimated Fuel	One Time Equipment	Rank Order Of Overall Feasibility
	Current (1979)	Near Term (1985-1990)	Cost of Fuel	Cost of Equipment	Cost Differential/yr	Cost Differential	
Low-Btu Gas From Coal	No	Yes	1.61	1.20	11,284	6,300	8
High-Btu Gas from Coal	Yes	Yes	1.70-2.09	1.0	12946-20159	0	10
# 1 Distillate Oil	Yes	Yes	1.34	1.43	6288	13,545	7
# 2 Distillate Oil	Yes	Yes	1.26	1.43	4808	14,545	5
# 5 Distillate Oil	Yes	Yes	1.40	1.50	1840	15,750	2
# 6 Distillate Oil	Yes	Yes	1.00	1.50	0	15,750	1
Kerosene	Yes	Yes	1.27	1.43	4993	13,545	6
Steam Coal (<1%) Conventional Boiler	No	Yes	0.56	6.0	0	157,500	14
Steam Coal (>3%) Conventional Boiler	No	Yes	0.49	7.0	0	189,000	15
Propane	Yes	Yes	1.15	1.45	2774	14,175	4
n-Butane	Yes	Yes	1.12	1.45	2219	14,175	3
Imported LNG	Yes	Yes	1.67	1.0	12,361	0	9
Coal Derived Steam	Yes	Yes	1.92	0	17,005	-	11
High-Btu Gas from Biomass	Yes	Yes	3.12	1.0	39,207	0	16
High Btu Gas from OTEC	Yes	Yes	7.14	1.0	113,553	0	17
# 2 Distillate Oil from Coal Derived Syn-Crude	Yes	Yes	2.47	1.43	27,186	13,545	13
Steam Coal (>3%) Fluidized Bed Boiler	Yes	Yes	0.49	5.75	0	149,625	12

N.A. = Not Applicable C.N.A. = Commercially Not Available

When firing urban solid waste or coal, the boiler heat transfer surfaces must be designed for lower heat release than would be the case for gaseous or liquid fuels, in order to avoid slagging. The combustion chambers must be sized to accommodate the coal-handling equipment (i.e., stokers, grates, ash pits). This larger and more complex conventional boiler system costs substantially more than a comparable output liquid- or gas-fired system. The cost of a solid fuel system is also increased by the cost of onsite storage and the fuel delivery system to the boiler. When firing a solid fuel that has a relatively high sulfur content ($>1\%$), the addition of expensive flue gas desulfurization equipment will be required in order to meet environmental air-quality standards. The cost of a conventional solid fuel-fired steam-generating system, applicable to the HAHP-ICES being evaluated, will be up to 6 or 7 times that of a natural-gas-fired system. However, the cost differential for larger-scale systems would not be as great because the fuel-handling components become a smaller part of the steam-generating cost for larger systems.

A potentially applicable alternative to conventional boilers, which has been successfully demonstrated with both urban and solid waste and coal, is the fluidized-bed boiler. This recently commercial technology is currently available from the Johnston Boiler Co., Ferrysburg, Michigan, in boiler sizes of 2,500 to 50,000 lbs/hr of steam for pressures up to 300 psig. These boilers have the advantage of being able to operate at slightly higher efficiencies than conventional boilers and are able to handle high-sulfur fuels in an environmentally acceptable manner. In the Johnston system, a bed of limestone or dolomite is fluidized at about atmospheric pressure in the combustion chamber. Within the combustion chamber, the limestone or dolomite reacts with oxygen and the sulfur dioxide generated during the combustion process. This approach achieves a sulfur dioxide removal rate in excess of 90%.

7.1.3 Recommendations and Conclusions on Alternative Fuels for Baseload Usage

Table 7.3 summarizes the feasibility of using alternative fuels to replace natural gas in the base-case HAHP-ICES. A number of fuels have been ruled out because they are in a form that cannot be used directly as boiler fuels. These excluded fuels include raw coal because of its sizing and cleaning requirement; all crude-type oil because of its variable composition; and all futuristic fuels, such as hydrogen and low-Btu gas, because the equipment or fuel is not yet commercially available. Alternative fuels are rank ordered by increasing costs for fuel-handling and steam-generating equipment and fuel purchases. In the base case, the annual fuel cost differential is the economic requirement to make the fuel cost of the alternative fuel the same as if natural gas were used. The annual fuel cost differential is based on the product of the ratio of the alternative fuel cost to natural gas and the annual cost of gas for the baseline case (\$18,494/year). The steam-generating equipment cost differential is the economic requirement that makes the alternative fuel system have the same effective cost as the steam generator in the HAHP central plant. The top five fuels in the rank order of Overall Feasibility column appear to be the most feasible as alternative fuels. The top five fuels are No. 6, No. 5, and No. 2 distillate fuels; n-butane; and propane. The additional steam-generating equipment cost for using these fuels over natural gas ranges from 43% to 50% and the additional yearly fuel costs over natural gas (assuming

a city-gate price of \$2.15/10⁶ Btu) ranges from 0% to 26%. These trends should also apply to the site-specific case.

From the point of view of the thermal utility, the use of alternative fuels adds complexity to the operation of the central plant. In addition to the operation of the turbine and heat pump, there are fuel storage and handling facilities, and perhaps environmental pollution control machinery. These complexities will raise operations and maintenance costs. Of course, flexibility is gained in terms of employing HAHP-ICES in areas where natural gas is unavailable.

The consumer must pay increased costs for thermal energy because of the increased fuel and equipment costs. Alternative fuels to natural gas are only economically viable if means are available to offset the increased costs of utilization of these fuels.

7.1.4 Alternative Fuels for Peakshaving

Several times over the past four years, the widespread occurrence of severely cold weather over the North-Central United States has created temporary shortages of natural gas. At a few locations, these shortages created emergency situations. The temporary shortages lasted from 2 to 7 days in almost every instance. They were due largely to capacity limitations in the natural gas transmission, compression and distribution systems in the region.

Natural gas is employed for space heating in over 65% of the residential dwelling units in the North-Central region. Peak-utility gas sendout rates during sub-zero weather typically reach 2 to 3 times the annual average gas sendout rate. Use of a peak-shaving fuel at HAHP-ICES installations during periods of severe weather would help relieve the demand for gas at these times.

This problem may be addressed by utilizing a boiler that has dual fuel capacities. A system that can fire natural gas and/or oil requires a liquid fuel storage system. The additional capital cost of the steam-generating system for maintaining a one-week emergency supply of oil or LPG fuel is roughly 50% greater than the base case natural-gas-fired system. This additional cost might be offset by Government subsidies or other means of supplying the initial capital cost differential for systems that can quickly convert to alternative fuels in times of national emergencies.

The use of alternative fuels for peakshaving results in added complexity to the thermal system; and, unless capital and operating cost differentials associated with dual fuel capabilities are subsidized or met by other means, thermal utility customers will have to pay the associated increased equipment, fuel, and operation and maintenance costs.

7.2 Alternative Prime Movers

An assessment of alternative prime movers is a logical variation in the HAHP-ICES concept that must be addressed since it allows additional applications design flexibility. Other primary-fueled drivers could, under some circumstances, provide a more favorable fit for specific community site requirements.

The two alternatives to the Rankine Steam System that could be developed near term for ICES are the open (Brayton) cycle gas turbine and the spark ignition (Otto Cycle) engine. (Near term in this context refers to the period through 1985.) The basic power requirement, less than 200 horsepower, makes the gathering of equivalent data more difficult because different prime movers are not always designed for the same type of service. Comparable information on capital costs and operational criteria (i.e., availability, reliability and maintenance requirements) for utility base load, continuous service, can only be obtained by extrapolation of data taken from generally similar machinery. Cost projections have to be tempered by expected production runs for a power unit. HVAC commercial size equipment would have manufacturing levels between those of industrial drivers and those of the automotive market where runs of 400,000 are not unrealistic. Where a particular type of engine requires additional development for a specific application, contingency costs play a part in inflating the price and make direct comparisons difficult.

The major performance differences between the Rankine, Brayton, and Otto Cycle drivers lie in the ratio of power to recoverable heat, power generation efficiency, overall efficiency and the temperature level of the recoverable heat. Table 7.4 shows these relationships for the three systems. The greater percentages of recoverable heat are from the condenser in the Rankine cycle and the unit exhaust in the case of the Otto and Brayton cycles. The smaller percentages are from the lube oil for the Rankine and Brayton and a combination of lube oil and block (jacket) cooling for the Otto engine.

Table 7.4. COMPARISON OF PERFORMANCE OF ALTERNATIVE
PRIME MOVERS FOR HAHP-ICES

	<u>Rankine</u> <u>(Steam)</u>	<u>Otto</u> <u>(Gas Engine)</u>	<u>Brayton</u> <u>(Gas Turbine)</u>
Power Level, hp (Continuous Duty)	90.0	90.0	90.0
Power Plant Efficiency, % (170°F Cond)	27.0	28.0	11.0
Fuel Consumption Btu/hr (HHV)	1.02×10^6	$.83 \times 10^6$	2.11×10^6
Recoverable Heat Btu/hr	0.58×10^6	$.37 \times 10^6$	1.2×10^6
% Recoverable Heat at Available Temperature Level, °F	95% @ 170.0	84% @ >250.0 16% @ <200.0	96% @ >300.0 4% @ <200.0
Overall Efficiency With Heat Recovery, %	79.0	72.0	68.0

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From Table 7.4, it becomes apparent why the Rankine cycle was selected: If all the condenser heat can be recovered, the Rankine system would give the highest overall efficiency. Where building heating requires a high delivery temperature, the Otto and Brayton cycles have distinct advantages. If the heating-to-cooling load ratio is high, the Brayton cycle may be preferred because it produces such a large amount of recoverable waste heat compared with its power output. The three prime movers have different sensitivities to ambient temperature, with the Brayton the most affected and the Rankine the least. The gas turbine exhibits a 4% improvement in power and a small efficiency improvement for a 10°F reduction in ambient temperature.

A problem in comparing the potential for alternative prime movers in the HAHP-ICES applications is that different prime movers are not always designed for the same type of service; industrial, utility, automotive, and aerospace, for example. Both natural gas spark ignition (Otto Cycle), engines, and natural-gas-fired (Brayton Cycle) gas turbines have been used successfully in total energy system (TES) applications but generally in the 1000 hp size or larger. A great deal of development has taken place in heavy-duty small diesel and spark ignition gaseous fuel and dual fuel engines for continuous duty applications. Small gas turbine development at the 200 hp level has been limited to aviation APU (auxiliary power unit) and military portable generator set uses. As a consequence, higher unit costs for small gas turbines reflect the large market differences and design requirements as well as the effect of production run quantities. A small diesel engine may have a production run of 100,000 units; a small gas turbine, 2000 units.

Both small reciprocating gas engines and gas turbines have exhibited 96% availability in generator set service in the U.S. Army. Because small heavy-duty diesel-type units are currently being customized for many high use applications (i.e., transport refrigeration/heating, irrigation, and/or marine), the same approach could be taken with the APU gas turbine. Basically, high operating hour applications have been met by a 10% power derating, increased cooling capacity (large oil sump), and protective controls. The available APU designs would need a complete design audit and possibly significant changes to meet the same design criteria. This additional effort to adapt a gas turbine design could have a significant payoff in terms of total system simplicity through fewer parts, less requirement for gearing, and reduced size. Table 7.5 gives qualitative data for the two alternative prime movers competing with the steam Rankine cycle. In the estimates of relative first costs of the alternative prime movers, it is assumed that all three systems are brought to the same point of development for this application. The gas turbine would require about the same development effort as the Rankine system. The small heavy-duty diesel converted to run on natural gas is already in production for industrial use and, therefore, would need much less developmental engineering work. Note that the relative cost for the Rankine cycle with and without heat recovery is the same since the steam condenser is an integral part of the system.

The qualitative comparison of alternative prime movers shows that Brayton cycle machines are significantly more expensive than Rankine cycle machinery. Although they have desirable attributes from the viewpoint of the thermal utility, in terms of fewer parts, and smaller size; gas turbines will cause increased capital costs for the HAHP-ICES.

Table 7.5. RELATIVE FIRST COSTS OF ALTERNATIVE
PRIME MOVERS FOR HAHP-ICES

	<u>Rankine</u>	<u>Otto</u>	<u>Brayton</u>
Relative Cost of Prime Mover Without Heat Recovery	1.0	0.6	0.8
Relative Cost of Prime Mover With Heat Recovery	1.0	0.8	1.3
Air Quality Control Capability (Rank)	(1)	(3)	(2)
Fuel Use (S = Solid, L = Liquid, G = Gas)	S, L, G	L, G	L, G
Expected Availability, %	98 (est.)	96	96
Design Speed, rpm	4,200	1,800	50,000

If a sufficient heat load exists for the large amount of waste heat produced from the gas turbine, then it might prove to be economically viable. However, in the context of the current load mix, the added waste heat might be a liability because of the load-following control philosophy. To track thermal loads, the large amount of waste heat will result in part-loading of both the heat pump and turbine, with the resultant part-load inefficiencies penalizing system performance. In addition, during the cooling season, large amounts of waste heat will be rejected at the cooling tower, consequently reducing the effective utilization of input energy.

In contrast to the gas turbine, Otto cycle engines are less expensive than Rankine cycle machines. Spark-ignition engines are more efficient than steam turbines and have less recoverable heat available. To achieve the same total heat output as the steam turbine-driven heat pump at an ambient temperature of 30°F, an additional heat input of 0.27×10^6 Btu/hr is required to supplement heat recovered from the Otto cycle engine. However, the total input to the spark-ignition engine is only 1.10×10^6 Btu/hr because of its initially lower input, compared with an input of 1.02×10^6 Btu/hr for the steam turbine. Thus, the spark-ignition engine requires only 8% more input energy to get the same performance as the steam turbine.

The use of an Otto cycle engine appears to benefit the thermal utility because it is a less complex machine with simpler controls required to allow load-following. The customer should also benefit in terms of the reduced capital cost of the prime mover. The installed cost of the 90-hp steam turbine driver with condenser is about \$60,000. An Otto cycle driver with heat recovery could be installed for a cost of about \$48,000,* for an initial cost saving of about \$12,000. The lower availability of the Otto cycle prime movers may result in a reduction in overall savings due to increased maintenance costs. Information on maintenance costs for small horsepower prime movers is scarce, but is important in the final determination of the most appropriate prime mover for the HAHP-ICES.

*Based on an uninstalled cost of 0.8 times the steam system cost (Table 7.5) and comparable installation costs for both prime movers of 1.7 times uninstalled factory cost.

The Otto and Brayton systems have no near-term potential for burning solid fuels, and their small combustion volumes make control of combustion gas contaminants difficult. The external combustion nature of the Rankine system, combined with the ability to treat the power fluid system during operation, indicates a potential for higher availability.

Depending upon the specific set of circumstances (community loads, fuel availability, etc.), an alternative to the steam driver may be desirable. Each case must be carefully analyzed to make that determination.

7.3 Electric Power Production

In the base HAHP-ICES concept, the heat-pump steam turbine is operated in a load-following mode that minimizes thermal energy wasted by the system.

In an alternative HAHP-ICES concept, the heat-pump steam turbine is base-loaded. When compressor loads are reduced below the full-load condition, a generator is used to load the steam turbine to its full load-output (90 hp), and electricity is generated. Sale of electricity to the utility is credited against purchased electric power.

The opportunity to baseload the turbine should simplify the controlling of the system because the pumped heat and turbine condenser heat no longer must be carefully balanced against the load. In this alternative, excess heat above thermal load requirements is rejected. The viability of this alternative is keyed to the price at which electricity can be sold. At a \$2/10⁶ Btu natural gas cost, a system with a 30% efficient driver must receive at least 3¢/kWhr just to pay for the gas assuming no credit for associated thermal energy. Electricity sold at a price that recoups the cost of gas and amortized equipment cost associated with electricity production should result in a HAHP-ICES competitive to the base concept.

An alternative configuration of the HAHP-ICES concept is to generate all power for parasitics. This results in a reduction in compressor size to make available sufficient power for the generator load and an associated reduction in system heating and cooling capacities. Additional controls are required to operate a system configured in this way because parasitic loads are sensitive to heating and cooling loads. Thus, the control philosophy must provide, for instance, satisfaction of parasitic loads as a priority with the associated system heating and cooling capacities produced by the remaining turbine horsepower available supplemented by conventional equipment.

As another alternative to the production of electricity for sale back to the utility, electricity generated may be used to electrolyze water to produce hydrogen. The hydrogen generated may be stored onsite in hydride storage beds. The hydride storage beds may then be discharged to provide hydrogen for combustion in the boiler to displace the use of natural gas, or the hydrogen may be used to produce electricity in a fuel cell. The process of storing hydrogen requires heat removal from the hydride material at useful temperatures for heating. Discharge of hydride storage requires heat removal at temperatures low

enough for space cooling. The use of an electrolyzer to produce hydrogen from excess electricity produced by the HAHP central plant thus provides the additional possibility of supplying additional heating and cooling capacity to the central plant. When a fuel cell is used in the central plant system, electricity may be generated to meet peak demands and thus avoid demand charges to the central plant; also, heat may be recovered from the fuel cell to help meet space heating thermal loads.

7.4 Alternative Heat Sources

The base heat-pump central plant concept achieves a higher heating COP when a cooling load is available during the heating season providing a heat source to the heat pump. A less restrictive alternative is the exclusive use of outside air as a heat source for applications, such as a residential load, where no opportunities for internal heat recovery exist. Of course, a lower heating COP results because of the lower source temperature.

Although outside air, a low-temperature heat source, is the most commonly available heat source to the heat pump system, the source temperature should be as high as possible to ensure the best performance of the HAHP-ICES concept. The cost of utilization of alternative sources must also be consistent with allowing good economic performance. Alternative heat sources to augment system heating COP, besides outside air and internal heat recovery, are: aquifers, lakes, earth, waste heat from industrial processes, or electric power generation, heat recovery from exhaust air, or low-temperature (<100°F) solar energy.

7.5 Alternative Cooling Machines

An alternative method of obtaining cooling in the HAHP ICES is to employ an absorption chiller actuated by turbine waste heat. The use of an absorption chiller may benefit the system through more efficient utilization of turbine condenser heat during the cooling season. Given the current load mix, the domestic hot-water load is sufficiently large to utilize most of the turbine condenser heat. Thus, an absorption chiller is not a viable alternative in this application. Another problem is that the capacity of an absorption chiller operating from available turbine condenser heat is only about 40 tons. In this capacity range, absorption chillers are very expensive. Thus, one needs a larger heat pump module to get chiller capacity over 100 tons in order to lower the dollar per ton cost of the absorption cooling unit.

In view of this, the use of the absorption chiller is of benefit where its cost can be amortized over a year-round cooling load, such as in Miami. An absorption chiller will increase the complexity and cost of the central plant, but in an application where the cost of the chiller may be amortized over a year-round cooling load, the cost to the customer might be lowered because of the efficient utilization of turbine condenser heat.

7.6 Multiple Compressors

The use of a single, large capacity compressor driven by the steam turbine results in significant part-load efficiency penalties. This may be circumvented by using multiple compressors, driven from a common engine, which will allow the tailoring of heating and cooling outputs to the load while minimizing part-load performance penalties. However, the multiple compressor approach introduces problems of system reliability, additional system complexity, and additional system controls. The energy savings associated with a multiple compressor system must be sufficiently large to offset the increased equipment costs or the customer will suffer increased utility bills.

7.7 Multiple Heat-Pump Evaporators

For operation in the cooling mode, specialized evaporators may be used. Typical chilled water exit temperature from evaporators is 44°F to ensure adequate dehumidification of the conditioned space. Because dehumidification is only a fraction (perhaps 25%) of the total cooling load, it is possible to have a chilled water loop at 44°F to provide dehumidification, and another loop, perhaps at 55°F, to provide sensible cooling. Each loop would have a compressor, one sized to the sensible cooling load, the other sized to the latent cooling load. A 20% improvement in cooling COP may be realized by operating the chiller at a 55°F leaving water temperature to provide the sensible cooling load requirement.

In the heating mode, the use of multiple evaporators may be preferred if a variety of heat sources is available. The goal is to be able to exploit as many heat sources as possible within the economic constraints imposed on the HAHP-ICES concept.

The use of specialized or multiple evaporators must be considered in light of increased capital costs and complexity of system operation. Energy savings must be sufficient to offset the increased costs associated with the use of this equipment.

7.8 Thermal Energy Storage

There are two primary types of thermal storage. The first is distributed storage, in which thermal energy is stored in the mass of the building structure as sensible heat, or in a phase change material, perhaps incorporated in the building materials, with energy storage as the latent heat of fusion of the phase change material. Distributed storage materials may effectively store heat by raising the temperature of the conditioned space to transfer heat into storage and they also store cold by the lowering of the temperature of the conditioned space to remove heat from storage. As a result, distributed storage components benefit the heat pump system in both heating and cooling modes by providing a buffer against rapid changes in thermal loads.

The second type of thermal storage is central storage. In central storage, heat may be stored as sensible heat in a large tank of water and cold stored as chilled water or ice. Thus, hot and cold storage function independently in the centralized storage of thermal energy and the design may include hot or cold storage, or both, as required by the application.

The effect of thermal storage on system performance is to allow the integration of the thermal outputs of the central plant over time. Loads in excess of system capacity are met by discharge of storage. Storage is charged when loads are small. System performance is benefitted because the heat pump unit may be run at full load and maximum efficiency much of the time. (The heat pump is "base-loaded.") Part-load penalties are thus avoided because storage can act as a load. Further, the discharge of storage to meet peak loads avoids the use of conventional HVAC equipment that requires purchased power, often at peak rates.

Storage may be short- or long-term. Short-term storage integrates system thermal output up to, for example, five days; long-term storage integrates system outputs over a longer time period — perhaps to the extent of storing winter cold (i.e., storage acts as evaporator for heat pump) to provide summer cooling or to store summer heat (e.g., storage acts as condenser for heat pump) for heating in the winter.

Distributed cold storage tends to be a short-term method because of limitations in component sizes. That is, there is a limit to how thick the walls and floors of the buildings may be in the case of mass storage, and a limit on how much phase change material can be designed into various building components.

Massive building structures have an advantage in that their design is well understood. A significant drawback is the cost of such a structure, although some of the costs may be attributable to the HVAC system; also, a degree of occupant discomfort is inevitable because the storage and discharge of sensible heat may be transferred to and from the storage material. By comparison, phase change materials are compact by virtue of their large energy storage density. Phase change materials may be incorporated in the structure of the building as ceiling tiles or encapsulated in concrete walls or floors; they also may be designed into the HVAC terminal units. Due to their constant melting point temperature, phase change materials have an advantage in that they allow the maintenance of the conditioned space at nearly constant temperature until they are almost 100% charged or discharged.

Although distributed cold storage provides sensible cooling, it does not provide dehumidification. A chilled water temperature of 44°F delivered to terminal units is still required to handle the latent cooling load.

Central cold storage may be accomplished in the short term by the use of chiller water storage, simply a large tank of cold (~44°F) water. Short-term cold storage would be used to meet summer cooling load peaks. Long-term cold storage may be used to store cold during the winter for summer cooling needs, in addition to heat pump output in the cooling mode. In the long term, the heat pump may be operated in an "ice-maker" mode. Particularly if ambient air is an alternative source of heat during the heating season, operation of an "ice-maker" heat pump results in improved COP in the heating mode because the heat source temperature is higher than the ambient air temperature and results in increased system capacity during the cooling season. A drawback of long-term cold storage is the extensive storage volume required.

Distributed heat storage may be accomplished in the same way as distributed cold storage — in massive building structures or in phase change materials. The operation of these components is analogous to distributed cold components and, in fact, the same components will benefit both heating and cooling modes. Storage is charged by raising the temperature of the conditioned space, and storage discharges as the space cools down. The issue of the negative impact of the temperature swing of the conditioned space during charging and discharging on occupant comfort is comparable to the problem with distributed cold storage components.

Central heat storage may be low-temperature or high-temperature. Low-temperature heat storage utilizes heat available at the heat pump condenser which is available at 130°F. The storage medium most likely to be used is water. High-temperature heat storage utilizes turbine exhaust heat which is available from 150° to 190°F, depending on ambient temperature.

A two-tank storage system maintains better performance during discharge by avoiding the continuously dropping discharge temperature associated with a well mixed, single-tank storage system. A two-tank system can also make good use of both heat pump condenser and turbine exhaust heat. Heat storage systems require the provision of large heat transfer surfaces to minimize impacts on sendout temperatures to the space heating system so that heat loads may be adequately served. Central heat storage components may be used exclusively or in conjunction with distributed heat storage components.

The use of thermal storage benefits the thermal utility by providing a buffer against rapid change in thermal loads. Because thermal storage acts as a load, system performance is benefitted because the system can operate at full load and maximum efficiency. Controls will be required to interface thermal storage and the rest of the central plant. The buffering effect of thermal storage may result in simplified control of the system because properly sized storage should provide a "home" for excess thermal energy so that requirements for the complexities of load-following operation are minimized. The discharge of thermal storage also offsets the use of conventional equipment to meet peak loads. Thermal storage is not free and benefits must be weighed against the cost of equipment and operating the thermal storage components.

The customers may suffer some inconvenience if distributed storage is used. That is, rather than the tightly controlled temperatures they are accustomed to, the temperature of the conditioned space may vary by ten or more degrees as storage is charged or discharged. Properly managed central storage will not cause any impact on the thermal comfort of the user. If the benefits of thermal storage to the operation of the HAHP-ICES are sufficiently great in terms of reduction in energy consumption, the customers' utility bills will not be any different than for the base central plant concept.

7.9 Summary

The following discussion is a summary of the primary impacts of variations in HAHP-ICES design on system economics and market penetration potential.

A variation in the design and/or operation of HAHP-ICES is of benefit if it reduces system complexity, increases reliability, increases convenience to the user, or lowers the customers' utility bills. A variation may also benefit the concept if, by tailoring the system to conform more closely with community requirements, it increases the potential market for the HAHP-ICES concept.

- Alternative Fuels

- The use of alternative fuels for HAHP-ICES is a benefit to the nation. It frees up a premium fuel — natural gas — for other uses.
- The use of alternative fuels for HAHP-ICES may increase its market penetration potential in areas where natural gas is unavailable.
- The use of alternative fuels has a negative impact on HAHP-ICES economics because fuel costs are greater than for natural gas and there is additional equipment cost associated with the utilization of alternative fuels for steam generation.

- Otto Cycle Drivers

- Otto cycle engines may benefit HAHP-ICES economics because they have lower initial costs than the steam turbine engine.
- Otto cycle engines are well-developed with proven reliability.
- The use of Otto cycle engines has little impact on system performance. However, system design must be carefully reviewed in terms of engine/compressor match (e.g., Otto cycle engines require reciprocating compressors, steam turbines may drive screw or turbo-compressors).

- Electricity Generation

- The generation of electricity by HAHP-ICES for anything beyond the minimal requirements of central plant parasitic loads negatively impacts on HAHP-ICES market potential because of the problems of the interface with the electric utility. This is an institutional problem.
- Electricity generation will generally improve the system's economics.

- Alternative Heat Sources

- The use of alternative heat sources to ambient air or internal heat recovery may improve system performance.
- Alternative heat sources may have negative impacts on HAHP-ICES economics and market penetration because of increased complexity and cost.

- Absorption chillers, driven by turbine condenser waste heat, are generally not economic unless their cost can be amortized over a long cooling season.

- Multiple compressors and evaporators improve system performance but at the price of increased system cost and complexity. Such variations cannot readily be justified.
- Thermal energy storage improves system performance through load-leveling. However, thermal energy storage equipment is bulky, expensive, and unfamiliar to many users. Thermal energy storage may not be a desirable alternative because of increased complexity and cost.

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8. COMPONENT TESTING REQUIREMENTS

The HAHP-ICES is a combination of state-of-the-art HVAC equipment and a unique heating and cooling source. The success of the system depends upon the reliable and efficient operation of this innovative design. To ensure that the initial demonstration will have the highest probability of proving the concept in service, those components that are critical to the concept must be individually tested, and their mechanical integrity, controllability, and thermodynamic performance must be verified.

The HAHP-ICES will consist of a number of core modules around which more conventional HVAC devices may be attached to tailor the heat pump to individual community requirements. These core modules will be factory assembled and tested wherever possible, to keep final installed cost to a minimum and to ensure as much of a competitive edge as possible with the currently used conventional designs. The major components or subsystems that will require specific tests before inclusion in a demonstration program are the mechanical refrigeration prime mover, the refrigeration loop, and the steam generator. These three subsystems are merged at the site, forming the core steam generator/driver/chiller unit, which is controlled to minimize the fuel gas input.

8.1 HAHP-ICES Core System

The following three components comprise the HAHP-ICES core system:

- Steam Generator
- Steam Turbine — Motor/Generator Drive
- Mechanical Chiller.

The Steam Generator is a compact, high-temperature, high-pressure unit sized to provide full design flow to the high-efficiency steam turbine with suitable over-temperature and over-pressure available for system tuning, safety margin, and allowance for performance degradation. The steam generator should undergo the following series of tests prior to integration with the expansion turbine and ancillary steam loop devices:

- Combustion Tests: These are a series of fire-side instrumented tests to determine burner combustion efficiency and flue gas contaminant levels at different heat-release levels. Measurements would be taken during simulated startup and shutdown, and for sustained load increments of 25%, 50%, 75%, and 100%. Particular attention would be given to HC, CO, NO_x, particulate, and visible smoke during transient operation.
- Performance and Control Tests: These consist of a series of bench tests that would be performed to study the structural and thermodynamic behavior of the generator. The package would consist of a full complement of strain gauges, thermocouples, and pressure transducers to monitor stress, metal temperatures, and transient pressures during various operational modes. This instrumentation would be in addition to feed-water/steam pressure, temperature, and flow measurement devices. Design deficiencies identified during these tests would be corrected and checked before they impacted upon demonstration unit reliability and future production units.

The steam turbine - motor generator driver is a sophisticated high-speed unit designed for low maintenance, semi-hermetic operation. The unit would undergo a series of mechanical integrity tests followed by operational control and performance tests. These tests would be performed in a production-oriented test cell, where deficiencies could be easily corrected or, if necessary, the unit could be returned to assembly for rework (balancing, clearance modification, etc.). These tests consist of the following:

- Preliminary checkout of auxiliaries (lube oil system, feed pumps, circulating pumps, etc.)
- Dynamic stability checkout using dummy turbine rotor and compressor rotor
- Dynamic checkout of the motor/generator and its clutching mechanism
- The driver package performance tested with the steam turbine driving the motor/generator as a generator to determine thermodynamic performance and loss levels.

The mechanical chiller compressor and its evaporator and condenser would be assembled with the driver to test the integrated power supply and load devices. The tests would be as follows:

- Separate performance tests of the refrigerant compressor, one using the electric motor as the driver, and the other using the Rankine steam system as the driver
- Performance and operational check of the complete unit to include the following:
 - a. System startup
 - b. Operating range of power output and efficiency
 - c. Shutdown
 - d. Overspeed trip checkout (protective devices)
 - e. Simulation of system upsets and off-design operation.

HAHP-ICES has a sophisticated control system to ensure operation at highest efficiency. The control system would undergo a series of tests under simulated conditions to ensure that operation of the system under all control modes is as expected.

Ancillary HAHP-ICES components unique to the system would also undergo tests. Among the most important of these are the water treatment, the non-condensable gas removal, and the cooling tower modules. Water quality from the makeup and condensate polishing equipment will be checked against acceptable values using a reference raw-water supply. After the above tests are performed on the prototype unit, test procedures will be generated for production systems and for the first site-demonstration tests.

The main purpose for the component testing requirements mentioned above is to ensure that the major subsystems are fully operational before linkup. This procedure minimizes the installation problems associated with startup and helps in the assessment of operational and performance deficiencies that may arise in the completed HVAC system.

9. DESCRIPTION OF ANALYSES

9.1 Thermal Characteristics of Buildings Served by HAHP-ICES

The base-case application of HAHP-ICES was a mixed load community consisting of one, 59,000 ft² office building; and five, 24-unit low-rise apartment buildings. The site-specific community served by HAHP-ICES consists of a load mix of 42 townhouse dwellings, 120 low-rise (five buildings) dwelling units, 520 high-rise (five buildings) dwelling units, 135,000 ft² of retail space under one roof, and 124,000 ft² of office space. In this section, we describe the thermal characteristics of the buildings that make up the site-specific community served by HAHP-ICES, and we also summarize the thermal loads for heating and cooling that the central plant must satisfy.

9.1.1 Townhouse, Low-Rise, and High-Rise

The thermal characteristics of these buildings are based on previous work done by IGT.*

The thermal characteristics of the residential structures are in accordance with the requirements of ASHRAE Standard 90-75. The conservation measures applied to the residential buildings, based on ASHRAE Standard 90-75, are detailed in Table 9.1. Construction parameters for the residential buildings are first characterized according to present-day construction practices, the so-called "generic" construction parameters. The changes made to bring the thermal characteristics of the residential buildings in line with ASHRAE 90-75 are then characterized and may be contrasted with the thermal characteristics of the "generic" designs. Applied to townhouse and to low-rise apartment structures, these measures were governed only by the heating-degree-days. Applied to high-rise structures, the conservation measures depended upon both the latitude and the heating-degree-days. Pertinent to all the structures, the Standard specifies limiting values for the combined thermal transmittance (U_o value) of wall and roof/ceiling and for the rates of air infiltration. Moreover, for the high-rise structure, the Standard sets a limiting value for the overall thermal transfer rate, in order to decrease the cooling load.

The low-rise structure and the townhouse required the addition of storm windows, in order to reduce the U_o value. The high-rise structure received a large number of conservation measures due to the excessive heating as well as cooling loads. The fenestration areas had to be cut in half in order to reduce the overall thermal transfer value.

* Whaley, T.P., Application Analysis of Solar Total Energy to the Residential Sector, Institute of Gas Technology, DOE Contract No. EG-77-C-04-3787, ALO-3787-3, Final Report, July 1979, Volume II.

Table 9.1. CONSERVATION MEASURES

<u>Townhouse</u>	<u>Low-Rise</u>	<u>High-Rise</u>
Reduce Infiltration	Reduce Infiltration	Reduce Infiltration
Add Storm Windows	Add Storm Windows	Decrease Window Surface Area
		Double Glaze Windows
		Increase Wall Insulation
		Increase Roof Insulation
		Variable Volume Ventilation

Floor plans and elevations of a two-story, three-bedroom townhouse are shown in Figures 9.1 and 9.2. Generic structural characteristics are shown in Table 9.2. Energy related parameters for a generic townhouse interior unit are shown in Table 9.3; and the energy related parameters for an energy conservative townhouse interior unit are shown in Table 9.4.

The floor plans of a two-story, low-rise building is shown in Figure 9.3. Note that the floor plan is for a 24-unit, low-rise building. Because in the previous IGT work thermal loads for the low-rises were generated for the 24-unit building, thermal loads for the evaluation of HAHP-ICES performance were generated on a per dwelling unit basis and multiplied by the number of dwelling units to arrive at the aggregate load.

Generic structural characteristics for the low-rise building are shown in Table 9.5. Energy related parameters for the generic low-rise building are shown in Table 9.6; and the energy related parameters for an energy conservative low-rise building are shown in Table 9.7.

The floor plan of a 15-story, 180-unit high-rise building is shown in Figure 9.4. Note that the community served by HAHP-ICES consists of five, high-rise buildings, each with 104 units, in six stories. Because in the previous IGT work thermal loads for the high-rise building were generated for the 180-unit building, thermal loads for the evaluation of HAHP-ICES performance were produced on a per dwelling unit basis and multiplied by the number of dwelling units to get the aggregate thermal loads.

Generic structural characteristics for the high-rise building are shown in Table 9.8. Energy related parameters for the generic high-rise building are shown in Table 9.9; and the energy related parameters for an energy conservative high-rise building are shown in Table 9.10.

Figure 9.1. FLOOR PLAN FOR A 3-BEDROOM, 2-STORY TOWNHOUSE

Figure 9.2 . PROFILE OF A 3-BEDROOM TOWNHOUSE

Table 9.2. GENERIC STRUCTURAL CHARACTERISTICS OF TOWNHOUSE RESIDENCES

Basic Design	2-story, 3-bedroom	
Foundation	Full basement	
Areas, sq ft	<u>Interior Unit</u>	<u>End Unit</u>
Total floor	1452	1452
Basement floor	726	726
Ceiling	763	763
Exterior wall	737	1348
Window glass	139	155
Patio door	60	60
Front door	20	20
Basement wall (ext.)	275	481
Exterior Wall Material		
Siding	Wood (1/2-in. x 8-in., lapped) 15-lb felt (building paper)	
Sheathing	1/2-in. plywood	
Insulation	Batt insulation, R-7, 1-in. air space	
Inside surface	1/2-in. gypsum	
Ceiling Material	1/2-in. gypsumboard, batt insulation, R-11	
Roof Material	1/2-in. plywood sheathing, 15 lb felt (building paper), asphalt shingle	
Windows (with draperies)	Single glaze, aluminum sash	
Patio door (with draperies)	Single glaze, aluminum slider	
Roof	Gable	

Table 9.3. ENERGY-RELATED PARAMETERS,
GENERIC TOWNHOUSE INTERIOR UNIT

1. "U" values	Wall	Roof	Door	Floor	Windows	* Patio Door*		
Btu/hr-sq ft-°F	0.092	0.070/0.066*	0.54	0.10	0.87/0.81	0.87/0.81		
2. Areas, sq ft		<u>North</u>	<u>East</u>	<u>South</u>	<u>West</u>			
Floor = 1452	Walls	0	352	0	385			
Ceiling = 763	Glass	0	108	0	91			
	Doors	0	0	0	20			
3. Winter Transmission Losses, Btu/hr	Walls	0	32(70-Temp)	0	35(70-Temp)			
Temp °F, Outdoor	Glass	0	94(70-Temp)	0	79(70-Temp)			
Ceiling = 54(70-Temp)	Doors	0	0	0	11(70-Temp)			
Basement = 2600								
4. Summer Transmission Gains, Btu/hr	Walls	0	32(75-Temp)	0	35(75-Temp)			
Temp °F, Outdoor	Glass	0	87(75-Temp)	0	74(75-Temp)			
Ceiling = 50(75-Temp)	Doors	0	0	0	11(75-Temp)			
5. Reference Solar Gains, Btu/hr	Total	Latitude	Walls	<u>North</u>	<u>East</u>	<u>South</u>	<u>West</u>	<u>Roof</u>
June 21 @ 2 p.m.	11,300	24°		0	800	0	0	
	11,300	32°	Glass	0	2300	0	5800	2400
	11,200	40°		0	2300	0	5800	2400
	11,000	48°		0	2300	0	5800	2300
			Doors	0	2200	0	5800	2200
				0	0	0	0	
6. Solar Area Percentages				0	50%	0	40%	10%
7. Winter Air Infiltration = 72 + 3.8 (70-Temp)								CF/min
8. Summer Air Infiltration = 97 CF/min								
9. Total Heat Gain From Cooking = 2700 Btu/hr								
10. Total Heat Gain From People = 2000 Btu/hr								

* Winter value/summer value.

Table 9.4. ENERGY-RELATED PARAMETERS, CONSERVATIVE TOWNHOUSE INTERIOR UNIT

1. U glass = 0.52/0.50, Others Unchanged

2. Areas Unchanged

3. Winter Transmission Losses, Btu/hr

Glass = 130 ΔT

Walls = 67 ΔT

Doors = 11 ΔT

Ceiling = 54 ΔT

Basement = 2600

4. Summer Transmission Gains, Btu/hr

Glass = 123 ΔT

Walls = 67 ΔT

Doors = 11 ΔT

Ceiling = 50 ΔT

5. Reference, Solar Gains

<u>Total</u>	<u>Latitude</u>	<u>Walls</u>	<u>E</u>	<u>W</u>	<u>Roof</u>
10,200	24		800	0	2400
10,200	32		2000	5000	2400
		<u>Glass</u>	2000	5000	2400
10,100	40		2000	5000	2300
10,100	48		2000	5000	2200

6. Solar Area, %

49%

39%

12%

7. Winter Infiltration = 39 = 0.9 ΔT CF/min

8. Summer Infiltration = 49 CF/min

Figure 9.3. FLOOR PLAN FOR LOW-RISE STRUCTURE

Figure 9.4. FLOOR PLAN FOR 15-STORY HIGH-RISE

Table 9.5. STRUCTURAL CHARACTERISTICS OF GENERIC LOW-RISE APARTMENTS

Arrangement	Twelve units around an enclosed stairwell. Three stairwells per building.	
Number of Stories	2	
Apartments	24 two-bedroom	
Areas, sq ft	<u>Int. unit</u>	<u>End unit</u>
Floor	1120	1120
Exterior Wall	482	734
Total glass	110	110
Doors, steel	20	20
Ceiling	1120	1120
Story height	9	9
Construction	Wood frame, 2 x 4 studs, on 16 in. center	
Foundation	Slab-on-grade	
Exterior Wall	Brick veneer, 1/2 in. insulation board, 3-1/2 in. fiberglass batts	
Interior Wall	1/2 in. gypsumboard, 2 x 3 studs on 16 in. center, 1/2 in. gypsumboard	
Roof	Gable	
Windows, patio	Single glazing, aluminum frames.	
Ceiling	Asphalt shingles, 3/8 in. plywood, air space, 6 in. fiberglass loosefill insulation, 1/2 in. gypsumboard	

Table 9.6. ENERGY-RELATED PARAMETERS FOR GENERIC TWO-STORY,
WOOD-FRAME, LOW-RISE STRUCTURE

	<u>Wall</u>	<u>Roof</u>	<u>Door</u>	<u>Floor</u>	<u>Windows</u>	<u>Patio Door</u>		
1. "U" Values Btu/hr-sq ft-°F	0.072	0.048/ 0.046*	0.67	0.10	0.87/0.81*	0.87/0.81*		
* Winter value/summer value.								
2. Areas, sq ft		<u>North</u>	<u>East</u>	<u>South</u>	<u>West</u>			
Floor = 26,880	Walls	2784/1008 ⁺	3000	2784/1008 ⁺	3000			
Ceiling = 13,440	Glass	0	1320	0	1320			
	Doors	240	0	240	0			
+ Facing stairwell/exposed to outside.								
3. Transmission Losses Btu/hr, Temp °F	Walls	110(70-Temp)	216(70-Temp)	110(70-Temp)	216(70-Temp)			
Outdoor, Ceiling	Glass	0	1150(70-Temp)	0	1150(70-Temp)			
= 650 (70-Temp),	Doors	35(70-Temp)	0	35(70-Temp)	0			
Slab = 27,000								
4. Transmission Gains Btu/hr, Temp °F	Walls	110(75-Temp)	216(75-Temp)	110(75-Temp)	216(75-Temp)			
Outdoor, Ceiling	Glass	0	1070(75-Temp)	0	1070(75-Temp)			
= 620 (75-Temp)	Doors	35(75-Temp)	0	35(75-Temp)	0			
5. Reference	<u>Total</u>	<u>Latitude</u>	<u>Walls</u>	<u>North</u>	<u>East</u>	<u>South</u>	<u>West</u>	<u>Roof</u>
Solar Gains,	146,600	24°		0	4800	300	0	
Btu/hr, June 21	146,600	32°		0	27,700	0	83,400	29,600
at 2 p.m.	145,300	40°		0	27,700	0	83,400	29,600
	142,600	48°	<u>Glass</u>	0	27,700	0	83,400	28,300
				0	26,400	0	83,400	26,900
			<u>Doors</u>	0	0	800	0	
6. Solar Area Percentages				0	42%	01%	46%	11%
7. Winter Air Infiltration = 2020 CF/min (Average)								
8. Summer Air Infiltration = 1620 CF/min (Average)								
9. Diversified Total Heat Gain From Cooking = 56,000 Btu/hr								
10. Total Heat Gain From People = 36,000 Btu/hr								

Table 9.7. ENERGY-RELATED PARAMETERS FOR CONSERVATIVE
TWO-STORY, WOOD-FRAME, LOW-RISE STRUCTURE

1. U glass = 0.52/0.50, Others Unchanged

2. Areas Unchanged

3. Transmission Losses, Btu/hr

Glass = 1699 ΔT

Walls = 652 ΔT

Doors = 70 ΔT

Ceiling = 650 ΔT

Slab = 27,000

4. Transmission Gains, Btu/hr

Glass = 1618 ΔT

Walls = 652 ΔT

Doors = 11 ΔT

Ceiling = 620 ΔT

5. Reference Solar Gains

Total	Latitude
131,800	24
131,800	32
130,500	40
128,000	48

Walls

E
4,800

S
300

W
0

Roof

24,000

72,300

29,600

24,000

72,300

29,600

Glass

24,000

72,300

28,300

22,900

72,300

26,900

Doors

0 800

42

1

45

12

6. Solar Area, %

7. Winter Air Infiltration = 1,440 CF/min (Average)

8. Summer Air Infiltration = 896 CF/min (Average)

Table 9.8. STRUCTURAL CHARACTERISTICS OF 180-UNIT
GENERIC HIGH-RISE RESIDENTIAL STRUCTURE

Arrangement	Rectangular structure, central hall on each floor, two stairwells, two elevators.				
Number of stories	15				
Basement	None				
Apartments	First floor: five one-bedroom, six two-bedroom. Other floors: six one-bedroom, six two-bedroom.				
Areas, sq ft	<u>Middle Apartments</u>	<u>Corner Apartments</u>	<u>Halls & Lobbies</u>	<u>Stairs & Elevator</u>	<u>Utility Rooms</u>
Floor	753/899 ^c	884	1551/1017 ^b	632	580/360 ^b
Exterior Wall	52/62 ^c	316	0	106/160 ^b	200/240 ^b
Roof ^a	754/899	884	1017	632	360
Window glass	168/208 ^c	244	192	0	192
Entrance doors	20	20	53	53	0
Story height	10	10	10	10	10
Construction frame	Reinforced concrete.				
Floors and roof deck	6" reinforced concrete.				
Exterior walls	4" concrete, 1" rigid insulation, air space, 1/2" gypsumboard.				
Roof	Built-up; felt bitumen composition, 1-1/2" rigid insulation, 2" concrete deck, air gap, 1/2" gypsumboard.				
Entrance doors	<u>Apartments</u>	<u>Lobby</u>	<u>Staircase</u>		
	Metal, 1/unit	Steel, 4	Metal, 3		
Windows	Single glazing, aluminum sliders.				

^a 20% of roof is occupied by penthouse and mechanical room.

^b First floor/other floors.

^c One-bedroom/two-bedroom.

Table 9.9. ENERGY-RELATED PARAMETERS FOR GENERIC HIGH-RISE STRUCTURE

	<u>Wall</u>	<u>Roof</u>	<u>Door</u>	<u>Floor</u>	<u>Windows</u>	<u>Patio Door</u>
1. "U" Values Btu/hr-sq ft-°F	0.200	0.146	0.67	0.10	0.87/0.81*	0.87/0.81*
* Winter value/summer value.						
		<u>North</u>	<u>East</u>	<u>South</u>	<u>West</u>	
2. Areas, sq ft						
Floor = 153,500	Walls	1380	11,520	1380	15,270	
Roof = 10,218	Windows	7320	11,280	7320	10,080	
3. Transmission Losses						
Temp °F, Slab =	Walls	276(70-Temp)	2304(70-Temp)	276(70-Temp)	3054(70-Temp)	
24,000, Roof =	Windows	6380(70-Temp)	9850(70-Temp)	6380(70-Temp)	8710(70-Temp)	
1500 (75-Temp)						
4. Transmission Gains,						
Btu/hr, Temp °F	Walls	276(75-Temp)	2304(75-Temp)	276(75-Temp)	3054(75-Temp)	
Outdoor, Roof =	Windows	5940(75-Temp)	9160(75-Temp)	5940(75-Temp)	8100(75-Temp)	
1500 (75-Temp)						
		<u>North</u>	<u>East</u>	<u>South</u>	<u>West</u>	
5. Reference	<u>Total</u> <u>Latitude</u>	0	51,400	1,100	0	<u>Roof</u>
Solar Gains, 1,327,600	24°	168,400	237,000	168,200	630,000	71,500
Btu/hr, June 1,371,600	32°	161,000	237,000	219,600	630,000	71,500
21, 2 p.m. 1,463,500	40°	146,300	237,000	329,500	630,000	68,200
1,603,500	48°	146,300	225,700	484,000	630,000	65,000
6. Solar Area Percentages		19%	33%	19%	28%	1%
7. Winter Air Infiltration = 5600 CF/min (Average)						
8. Summer Air Infiltration = 4400 CF/min (Average)						
9. Ventilation = 18,500 CF/min						
10. Total Heat Gain From Cooking = 420,000 Btu/hr						
11. Total Heat Gain From People = 225,000 Btu/hr						

Table 9.10. ENERGY-RELATED PARAMETERS FOR CONSERVATIVE HIGH-RISE STRUCTURE

1.	U wall = 0.18,	U glass = 0.60,	U roof = 0.07			
2.	Areas, ft ²	<u>N</u>	<u>E</u>	<u>S</u>	<u>W</u>	
	Walls	5040	17160	5040	20310	
	Windows	3660	5640	3660	5040	
3,4.	Transmission Losses and Gains, Btu/hr					
	Walls	9,000 ΔT		Roof	700 ΔT	
	Windows	10,800 ΔT		Slab	24,000 (Losses)	
5.	Total Reference Solar Gains 670,000 Btu/hr					
6.	Solar Area, %	<u>N</u>	<u>E</u>	<u>S</u>	<u>W</u>	<u>Roof</u>
		17	39	17	25	2
7.	Average Winter Infiltration = 6500 CF/min					
8.	Average Summer Infiltration = 3000 CF/min					
9.	Ventilation = 4600 CF/min					

The indoor temperature in winter was maintained at 70°F. The transmission losses were proportional to the difference between 70°F and the outdoor temperature. The proportionality constant was set according to the particular building, and the outdoor temperature was obtained from the appropriate weather tape. Similarly, the summertime transmission gains were based on an indoor temperature of 75°F, so that these gains were proportional to the outdoor temperature less 75°F. Thermal gains and losses for alternative indoor temperatures may be determined by substituting the desired indoor temperature in the relationships for thermal gains or losses. The summer proportionality constant was slightly lower than the winter value due to lower "U" values of the roof and of the fenestration (window areas).

The solar heat gains would depend upon the intensity of solar radiation received at the building surfaces and upon several factors relating to the building. The method used in calculating the solar heat gains followed closely the one described in the ASHRAE Handbook of Fundamentals. An appropriate shading coefficient was applied to the solar heat gains at the window surfaces to account for the internal shading due to draperies made of semi-open weave fabric with medium-colored yarn. External shadings due to adjacent buildings or trees were not taken into account in this study.

In order to calculate the "unlagged" solar heat gain at any fenestration, we used the following equation:

$$\begin{array}{l} \text{Solar} \\ \text{Heat} \\ \text{Gain} \end{array} \begin{array}{l} (\text{Btu/hr-sq ft}) \\ = \\ \end{array} \begin{array}{l} \text{Shading} \\ \text{Coefficient (SC)} \\ \text{for Fenestration} \end{array} \begin{array}{l} \text{Solar Heat Gain Factor (SHGF)} \\ \text{X for Given Orientation} \\ \text{and Existing Conditions} \end{array} \quad (1)$$

We have calculated the solar heat gains at 2 p.m. on June 21 and used these gains as a reference for calculating the solar heat gains at other hours. For example, the solar heat gain (unlagged) at the west window will be equal to:

$$\begin{array}{l} \text{Solar gain (Btu/hr-sq ft)} \\ \text{SC} \end{array} \begin{array}{l} = \\ \end{array} \begin{array}{l} 0.6 \text{ X } 145 \\ \text{SHGF} \end{array} = 87 \quad (2)$$

While the convective portion of the instantaneous heat gain at the fenestration could be considered as instantaneous cooling load, the radiant portion due to building thermal storage had to be spread uniformly over 4 hours, including the given hour. The lagging time was appropriate to lightweight construction. Table 9.11 includes the lagging data for the vertical as well as for the horizontal surfaces. Consequently, the table of Solar Heat Gain Factors had to be modified to take this storage effect into account.

Table 9.11. REFERENCE SOLAR HEAT GAINS (Btu/hr-sq ft)

Glass (Single glaze, 11m shades, 95% clearance, 3-hour lag.)

<u>Latitude</u>	<u>N</u>	<u>E</u>	<u>S</u>	<u>W</u>
24°	23	21	23	63
32°	22	21	30	63
40°	20	21	45	63
48°	20	20	66	63
<u>Walls/Doors</u>	0/0	1.6/15	0.3/3	0/0

Roof

<u>Latitude</u>	<u>Roof</u>
24°	2.2
32°	2.2
40°	2.1
48°	2.0

Lagging Data

Vertical-Windows

55% First hour
3-hour spread
Uniform type spread

Horizontal-Roof

10% First hour
9-hour spread
Uniform type spread

The solar heat gains at the roof surface were lagged (i.e., adjusted to reflect a time lag) in order to correlate well* with the difference between the Total Equivalent Temperature Difference (TETD) and the actual indoor-outdoor temperature difference. This correlation works best if we spread the gains uniformly over 10 hours, including the given hour (9-hour spread) as shown in Table 9-12.

Table 9.12. ROOF SOLAR HEAT GAINS

Time	$\alpha I_t/h_o$ *, °F	10%, 9-hour spread†, °F	TETD‡ °F	TETD (Temp-75), °F
1	0	10.0	11	10
2	0	4.8	4	3
3	0	1.4	-1	-1
4	0	0.0	-6	-5
5	0	0.0	-7	-6
6	14	1.4	-4	-3
7	34	4.8	0	0
8	52	10.0	1	-1
9	67	16.7	10	5
10	79	24.6	19	11
11	86	33.2	31	19
12	89	42.1	43	27
13	86	50.7	54	36
14	79	58.6	65	46
15	67	65.3	71	51
16	52	69.1	76	57
17	34	69.1	74	56
18	14	65.3	72	56
19	0	58.6	62	50
20	0	50.7	53	43
21	0	42.1	43	35
22	0	33.2	33	27
23	0	24.6	25	21
24	0	16.7	18	16

* This is a term that is proportional to the absorbed solar energy at the outer surface of the roof.

† Ten percent of the absorbed energy is sensed by the cooling system; the remaining 90% is spread over the next 9 hours, reflecting a 9-hour time lag.

‡ Total Equivalent Temperature Difference — a term that accounts for storage of thermal energy in the building, considering both convection and radiation. These values, obtained from the literature, are derived by a "thermal response method" of calculation.

* i.e., proportional to the difference.

Thus, data in Columns 3 and 5 in Table 9.12 should show a good correlation, because subtracting (75-temp) from TETD produces a value that reflects the solar contribution to the total. This correlation, given graphically in Figure 9.5, shows that the heat gains from the roof surface reach a maximum between the hours of 4 p.m. to 6 p.m., although the Solar Heat Gain Factor is at a maximum at 12 noon.

Figure 9.5 . ROOF SOLAR GAINS PROFILE

The rates of air infiltration in winter are generally higher than those in summer, because air infiltration increases with an increasing indoor-outdoor temperature difference, which is generally higher in winter than in the summer for most of the selected cities. Summer air infiltration is generally in the neighborhood of 0.4 air changes per hour, while winter air infiltration can exceed 1 air change per hour in cold climates. Air infiltration is also increased with increased wind speed, which is generally higher in winter than in the summer. As a result, the rates of air infiltration in air changes per hour have been expressed as functions of the indoor-outdoor temperature difference, with the wind speed kept constant at 15 mph in winter and at 7.5 mph in summer. These rates were multiplied by the volume of the air-conditioned space to get the total rate of air infiltration. The results in units of cubic feet per minute (CF/min) were included in Tables 9.3, 9.4, 9.6, 9.7, 9.9 and 9.10.

Air infiltration has been determined experimentally to be temperature-dependent in winter for townhouse structures; this is reflected in the winter air-infiltration terms used in Tables 9.3 and 9.4. Although summer air infiltration rates show a slight dependence upon temperature difference, the dependence is so slight that the infiltration rate can be considered constant. This explains the lack of a ΔT term for summer air infiltration rates in Tables 9.3 and 9.4. Information on temperature-dependence is not available for low-rise and high-rise apartment buildings, so average ASHRAE values for both summer and winter air-infiltration rates were used in Tables 9.6, 9.7, 9.9 and 9.10 for low-rise and high-rise apartment buildings.

The remainder of the energy-related parameters included the internal heat gains from the kitchen appliances, which were assumed to follow the diversified cooking profile, and the internal heat gains from people, which followed the occupancy profile.

9.1.2 Retail Store

The retail store space in the site-specific community consists of a single-story building of 135,000 ft² floor area under one roof. The load estimate for the retail store was derived from the performance of a 4,000 ft² retail store of established thermal characteristics in terms of its dimensions (20 X 200 ft), lighting, and occupancy. The aggregate thermal load was derived by multiplying the loads by the appropriate factor ($135,000 \text{ ft}^2 / 4,000 \text{ ft}^2 = 33.75$). The operating characteristics of the retail store are summarized in Table 9.13.

9.1.3 Office Building

The office building in the site-specific community is a structure with 124,000 ft² of floor area in six stories. The building has been treated as having comparable thermal characteristics to the six-story, 59,000 ft² office used in the base case. Thus, the thermal loads were estimated to be 2.1 times ($= 124,000 \text{ ft}^2 / 59,000 \text{ ft}^2$) the thermal loads of the office building used in the base case. Building design parameters are shown in Table 9.14.

Table 9.13. RETAIL STORE THERMAL LOAD ESTIMATE (Pittsburgh)

Area = 4000 ft²/store (200 x 20 ft)

Total Area = 135,000 ft²

Load Multiplier = 33.75

Occupancy: 11 hours/day, 6 days/week

HVAC Operating Schedule

I) Business Days (Monday thru Saturday)

A) Outside Air Shut-Off Hours (heating mode)

10 hours after midnight

3 hours before midnight

B) Heating System Setback By 10°F

Months of January, February, March, April, October, November, December

10 hours after midnight

3 hours before midnight

C) Heating System Should Be Shut-Off

Months of May, June, July, August, September

10 hours after midnight

3 hours before midnight

D) Cooling System Shut-Off During January, February, March, November, December

E) Cooling System Shut-Off Hours During April, May, June, July, August, September, October

10 hours after midnight

3 hours before midnight

II) Sunday

A) Shut-Off Heating System All Day During Months of May, June, July, August, September

B) Heating System Setback by 10°F — All Day Months of January, February, March, April, October, November, December

C) Shut-Off Outside Air All Day for All Months

D) Cooling System Shut-Off All Day for All Months

No Domestic Hot Water is Provided

Table 9.14 Part 1. ENERGY RELATED DESIGN PARAMETERS
FOR OFFICE BUILDING

AREA: 70' X 140' = 9800 Sq. Ft. per Floor
6 Story
5 Above Grade
Floor to Floor = 10'

GLASS AREAS:

Floors 2 through 6

E = 540 Sq. Ft.
N = 180 " "
W = 450 " "
S = 180 " "

First Floor

E = 540 Sq. Ft.
N = 180 " "
W = 0 " "
S = 180 " "

GLASS TYPE:

Assume PPG Solargray
Twindow
Winter nighttime U = .48
Summer daytime U = .57
Shading
coefficient = .62

WALL AREAS - NET:

Floors 2 through 6

E = 860 Sq. Ft.
N = 520 " "
W = 950 " "
S = 520 " "

First Floor

E = 1860 Sq. Ft.
N = 520 " "
W = 1400 " "
S = 520 " "

WALL CONSTRUCTION:

Masonry - Dark Color
U = .09

Table 9.14 Part 2. ENERGY RELATED DESIGN PARAMETERS
FOR OFFICE BUILDING

INTERIOR WALLS:

Pre-Fab, Particle board core,
2" Thick
 $U = .18$

ROOF CONSTRUCTION:

Metal Deck
3" Rigid Insulation
No Ceiling - Used as Plenum Space
Heat Flow Up (Winter) $U = .11$
Heat Flow Down (Summer) $U = .10$

INTERNAL LOADS:

People:

245 BtuH Sensible
205 BtuH Latent

Occupancy:

Private Office Space 125 Sq. Ft. per Person
General Office Space 110 Sq. Ft. per Person
Stenographic Areas 85 Sq. Ft. per Person
Assume an average of 100 Sq. Ft. per Person
with a 75% Diversity Factor

Lighting:

3 to 4 Watts/Sq. Ft. Fluorescent

Business Machines:

20 KW per Floor Maximum

Ventilation Air:

10 to 15 CFM per Person

9.1.4 Determination of Domestic Hot Water Loads in Community Served by HAHP-ICES; Base and Site-Specific Cases

Domestic hot water loads for the office building served by HAHP-ICES were determined on an hourly basis by the following equation:

$$\text{Hourly Domestic Hot Water Demand (Btu/hr)} = [\text{Peak Demand (Btu/hr)}][\text{Percentage Variation Profile}][\text{Reduction Factor}][1/100.0]$$

The peak demand was determined assuming a domestic hot water temperature of 140°F and a temperature rise associated with the lowest inlet temperature of the cities served by HAHP-ICES; in this case, Chicago had the lowest inlet temperature of 32.4°F. Peak domestic hot water demands are summarized in Table 9.15. No domestic hot water is provided to the site-specific case retail space.

Table 9.15. PEAK DOMESTIC HOT WATER DEMANDS

Low-Rise (Base Case)	7.250×10^5 Btu/hr
Low-Rise (Site-Specific Case)	7.250×10^5 Btu/hr
Towhouse (Site-Specific Case)	2.940×10^5 Btu/hr
High-Rise (Site-Specific Case)	3.150×10^6 Btu/hr
Office (Base Case)	6.499×10^4 Btu/hr
Office (Site-Specific Case)	1.370×10^5 Btu/hr

The percentage variation profile for the base and site-specific case office buildings are presented in Table 9.16. The percentage variation profile represents the hourly pattern of hot water usage. Domestic hot water reduction factors reflect the monthly variation in inlet water temperature to domestic water heaters. A value for the reduction factor of less than one means that the inlet water temperature in that month is warmer than for the coldest month and hence, the energy required to supply domestic hot water in that month is reduced. Domestic hot water reduction factors for the office building (base and site-specific cases) are as follows:

<u>Month</u>	<u>Reduction Factor</u>
January	1.0
February	1.0
March	0.95
April	0.90
May	0.80
June	0.85
July	0.80
August	0.80
September	0.85
October	0.90
November	0.93
December	0.95

Table 9.16. PERCENTAGE VARIATION PROFILES; OFFICE BUILDING*

<u>Hour</u>	<u>Weekday, %</u>	<u>Saturday, %</u>
12:00 am	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0	0
8	0	0
9	53	10
10	53	10
11	53	10
12:00 pm	100	20
13	100	20
14	53	10
15	53	0
16	53	0
17	53	0
18	53	0
19	20	0
20	20	0
21	0	0
22	0	0
23	0	0

* No domestic hot water use on Sundays or Holidays.

The values presented assume comparable seasonal patterns for city water temperatures for all cities for which HAHP-ICES performance was evaluated.

Domestic hot water loads for the residential buildings served by HAHP-ICES were determined on an hourly basis by the following equation:

$$\text{Hourly Domestic Hot Water Demand (Btu/hr)} = [\text{Peak Demand (Btu/hr)}] [\text{Percentage Variation Profile}] [1/100.0]$$

The percentage variation profile for the townhouse and high-rise buildings is presented in Table 9.17. The percentage variation profile for the low-rise building is presented in Table 9.18. The seasonal characteristic of residential percentage variation profiles reflect the combined effects of differing patterns of domestic hot water use as a function of season and the monthly variation in inlet water temperatures.

A more precise approach to determining domestic hot water loads may be accomplished using the following equation for hourly domestic hot water demand (although the preceding methods were actually used in the determination of DHW loads):

$$\text{Hourly Domestic Hot Water Demand (Btu/hr)} = [\text{Peak Demand (Btu/hr)}] [\text{Percentage Variation Profile}] [\text{Reduction Factor}] [1/100.0]$$

The monthly water temperatures used to derive the domestic hot water reduction factors are reported in Table 9.19. Domestic hot water reduction factors were computed from the formula:

$$\text{Domestic Hot Water Reduction Factor} = \frac{(140 - \text{City Water Temperature})}{(140 - 32.4)}$$

Domestic hot water reduction factors are reported in Table 9.20.

Table 9.17. PERCENTAGE VARIATION PROFILES;
TOWNHOUSE AND HIGH-RISE BUILDINGS

<u>Hour</u>	<u>Winter, Spring, Fall</u> [*]	<u>Summer</u> [†]
12:00 am.	45	37
1	45	23
2	26	23
3	26	23
4	26	23
5	26	28
6	26	41
7	45	41
8	45	85
9	93	78
10	85	70
11	76	70
12	76	70
13	76	46
14	55	46
15	49	46
16	49	46
17	49	46
18	49	66
19	72	76
20	83	69
21	75	47
22	53	47
23	53	47

* January, February, March, April, May, October, November, and December.

† June, July, August, and September.

Table 9.18. PERCENTAGE VARIATION PROFILES; LOW-RISE

<u>Hour</u>	<u>January, February November, December</u>	<u>March, April, May, October</u>	<u>June, July, August, September</u>
12:00 am	45	50	31
1	45	50	31
2	25	23	18
3	25	23	18
4	25	23	18
5	25	23	18
6	30	23	18
7	45	40	32
8	45	40	32
9	93	82	63
10	85	75	63
11	76	68	53
12:00 pm	76	68	53
13	76	68	53
14	49	49	39
15	49	41	33
16	49	41	33
17	49	41	33
18	49	50	40
19	72	70	51
20	83	70	59
21	75	67	53
22	53	47	37
23	53	47	37

Table 9.19. CITY WATER TEMPERATURES

<u>Month</u>	<u>Atlanta</u>	<u>Chicago</u>	<u>Kansas City</u> °F	<u>Minneapolis</u>	<u>Pittsburgh</u>
January	38.0	32.4	35.0	36.5	39.0
February	35.0	32.7	36.0	37.4	39.0
March	45.0	35.2	46.0	41.0	40.0
April	54.0	42.7	54.0	51.8	51.0
May	56.0	50.3	61.0	66.2	61.0
June	60.0	56.6	72.0	68.9	73.0
July	65.0	62.3	78.0	78.8	78.0
August	65.0	64.4	78.0	77.9	80.0
September	62.0	62.5	72.0	74.3	77.0
October	58.0	55.9	58.0	53.6	63.0
November	55.0	45.6	43.0	41.0	55.0
December	35.0	35.0	36.0	35.1	44.0

Table 9.20. DOMESTIC HOT WATER REDUCTION FACTORS

<u>Month</u>	<u>Atlanta</u>	<u>Chicago</u>	<u>Kansas City</u> °F	<u>Minneapolis</u>	<u>Pittsburgh</u>
January	0.95	1.00	0.98	0.96	0.94
February	0.98	1.00	0.97	0.95	0.94
March	0.88	0.97	0.87	0.92	0.93
April	0.80	0.90	0.80	0.82	0.83
May	0.78	0.83	0.73	0.69	0.73
June	0.74	0.78	0.63	0.66	0.62
July	0.70	0.72	0.58	0.57	0.58
August	0.70	0.70	0.58	0.58	0.56
September	0.72	0.72	0.63	0.61	0.59
October	0.76	0.78	0.76	0.80	0.72
November	0.79	0.88	0.90	0.92	0.79
December	0.93	0.98	0.97	0.98	0.89

9.2 Summary of Thermal Loads

The monthly building thermal loads used in the base-case analysis are presented in Table 9.21. The sensitivity of the HAHP-ICES to changes in geographic locations necessitated the base-case communities' thermal requirements to be calculated. The resulting thermal loads for community location of Minneapolis, Kansas City, and Atlanta are shown in Tables 9.22, 9.23, and 9.24, respectively. In the study of the sensitivity of HAHP-ICES performance and economics to changes in geographic location, domestic hot water loads for all locations were assumed to be the same as for Chicago. Domestic hot water loads presented in Tables 9.22, 9.23, and 9.24 have been adjusted by the methods of Section 9.1.4 to reflect actual DHW energy requirements.

Table 9.21. MONTHLY BUILDING THERMAL LOADS
FOR BASE-CASE COMMUNITY LOCATION: CHICAGO

	<u>Office Building Loads</u>			<u>Residential Building Loads (Each)</u>	
	<u>10⁶ Btu</u>			<u>10⁶ Btu</u>	
	<u>Heating</u>	<u>Cooling</u>	<u>DHW</u>	<u>Heating</u>	<u>DHW</u>
January	176.1	158.2	9.2	142.8	58.3
February	128.2	165.9	8.4	97.9	52.6
March	136.7	186.2	8.0	98.7	53.0
April	70.9	261.4	8.5	31.4	51.2
May	46.5	285.7	8.1	8.0	53.0
June	0	439.6	7.1	0	39.8
July	0	531.5	7.3	0	41.1
August	0	463.5	7.4	0	41.4
September	0	352.8	7.4	0.1	39.8
October	81.8	265.4	8.6	40.7	53.0
November	98.0	194.7	7.8	63.6	56.4
December	148.6	154.2	8.3	118.6	58.3
Annual	886.9	3,459.1	95.9	601.9	597.9

The average and peak thermal loads for the buildings making up the site-specific community are summarized in Tables 9.25 and 9.26. Thermal loads for all buildings were developed using the Meriwether Code. The weather year used to develop the loads for Pittsburgh climate was 1961. Heating and cooling degree days are within 3% of the ten-year average heating and cooling degree days. The monthly Monroeville community thermal loads are shown in Table 9.27.

Table 9.22. MONTHLY BUILDING THERMAL LOADS FOR BASE-CASE
SENSITIVITY ANALYSIS, COMMUNITY LOCATION: MINNEAPOLIS

	<u>Office Building Loads</u>			<u>Residential Building Loads (Each)</u>	
	<u>10⁶ Btu</u>			<u>10⁶ Btu</u>	
	<u>Heating</u>	<u>Cooling</u>	<u>DHW</u>	<u>Heating</u>	<u>DHW</u>
January	230.9	128.5	8.8	203.7	56.0
February	191.1	141.1	8.0	163.9	50.0
March	163.4	160.8	7.6	130.3	50.4
April	98.8	234.3	7.5	49.5	46.6
May	43.0	291.1	6.7	9.2	44.0
June	0	445.2	6.1	0	33.8
July	0	448.7	5.8	0	32.5
August	0	461.7	6.1	0	34.1
September	0	293.7	6.3	0.9	33.8
October	44.8	273.1	8.9	7.7	54.6
November	130.7	165.2	8.2	97.0	59.2
December	179.4	136.7	8.3	149.5	58.3
Annual	1,082.2	3,180.1	88.2	811.9	553.2

Table 9.23. MONTHLY BUILDING THERMAL LOADS FOR BASE-CASE SENSITIVITY
ANALYSIS, COMMUNITY LOCATION: KANSAS CITY

	<u>Office Building Loads</u>			<u>Residential Building Loads (Each)</u>	
	<u>10⁶ Btu</u>			<u>10⁶ Btu</u>	
	<u>Heating</u>	<u>Cooling</u>	<u>DHW</u>	<u>Heating</u>	<u>DHW</u>
January	169.6	163.6	9.0	137.0	57.1
February	99.3	185.7	8.2	61.8	51.0
March	91.9	210.9	7.2	50.3	47.7
April	52.8	258.1	7.4	24.8	45.7
May	14.9	333.4	7.1	0	46.6
June	0	467.8	5.8	0	32.2
July	0	626.1	5.9	0	33.3
August	0	575.6	6.1	0	34.1
September	0	388.5	6.5	0	35.0
October	47.0	270.5	8.3	15.5	51.4
November	92.9	193.6	8.0	54.1	58.6
December	110.0	182.5	8.2	73.7	57.7
Annual	678.5	3,856.6	87.7	417.4	550.49

Table 9.24. MONTHLY BUILDING THERMAL LOADS FOR BASE-CASE
SENSITIVITY ANALYSIS, COMMUNITY LOCATION: ATLANTA

	<u>Office Building Loads</u>			<u>Residential Building Loads (Each)</u>	
	<u>10⁶ Btu</u>			<u>10⁶ Btu</u>	
	<u>Heating</u>	<u>Cooling</u>	<u>DHW</u>	<u>Heating</u>	<u>DHW</u>
January	95.7	210.2	8.7	50.7	55.4
February	70.1	216.4	8.2	28.1	51.6
March	47.9	259.9	7.3	10.1	48.2
April	15.7	331.3	7.4	0	45.7
May	1.5	389.8	7.6	0	49.8
June	0	441.1	6.7	0	37.8
July	0	563.7	7.1	0	39.9
August	0	593.3	7.4	0	41.1
September	0	464.7	7.4	0	39.8
October	29.5	313.8	8.3	0.06	51.4
November	63.6	230.1	7.0	19.9	50.8
December	95.5	200.2	8.3	53.5	58.3
Annual	419.6	4,214.7	91.5	162.5	569.7

Table 9.25. AVERAGE AND PEAK HEATING LOADS (JANUARY, FEBRUARY, DECEMBER): SITE: PITTSBURGH, PENNSYLVANIA

Weather year: 1961

Heating-Degree-Days = 6104.5 (per year)
6025.1 (10-year average)

Building Type	Floor Area Per Apartment (ft ² /apartment)	Total Area Per Building (ft ²)	Total Area In Community (ft ²)	Average Heat Load Per Square Foot (Btu/ft ² /hr)	Total Average Heat Load (Btu/hr)	Peak Heat Load Per Square Foot (Btu/ft ² /hr)	Total Peak Heat Load (Btu/hr)
Low-Rise (120 Units)	1120	26,880	134,400	6.56	8.817×10^5	16.72	2.247×10^6
Townhouse (42 Units)	1452	1452	60,984	7.73	4.714×10^5	19.80	1.207×10^6
High-Rise (520 Units)	853	88,869	443,444	6.97	3.091×10^6	16.42	7.281×10^6
Retail Store	-	135,000	135,000	18.04	2.435×10^6	28.00	3.780×10^6
Office	-	124,000	124,000	3.65	4.526×10^5	19.52	2.420×10^6

Table 9.26. AVERAGE AND PEAK COOLING LOADS (JULY, AUGUST, SEPTEMBER); SITE: PITTSBURGH, PENNSYLVANIA

Weather year: 1961

Cooling-Degree-Days = 627.1 (per year)
648.5 (10-year average)

Building Type	Floor Area Per Apartment (ft ² /apartment)	Total Area Per Building (ft ²)	Total Area In Community (ft ²)	Average Cooling Load Per Square Foot (Btu/ft ² /hr)	Total Average Cooling Load (Btu/hr)	Peak Heat Load Per Square Foot (Btu/ft ² /hr)	Total Peak Cooling Load (Btu/hr)
Low-Rise (120 Units)	1120	26,880	134,400	4.81	6.465×10^5	16.8	2.258×10^6
Townhouse (42 Units)	1452	1452	60,984	6.39	3.897×10^5	22.2	1.354×10^6
High-Rise (520 Units)	853	88,689	443,444	5.00	2.217×10^6	16.68	7.397×10^6
Retail Store	-	135,000	135,000	13.36	1.804×10^6	27.48	3.710×10^6
Office	-	124,000	124,000	16.95	2.102×10^6	54.0	6.696×10^6

Table 9.27. MONTHLY MONROEVILLE COMMUNITY THERMAL LOADS

	<u>Heating</u>	<u>Cooling</u>	<u>DHW</u>
		10 ⁶ Btu	
January	5,878.1	284.5	1,556.3
February	3,724.6	306.5	1,406.0
March	2,816.5	370.6	1,527.3
April	2,386.7	416.7	1,479.5
May	777.9	763.6	1,527.5
June	0	1,398.7	1,318.9
July	0	2,094.9	1,362.7
August	0	2,130.1	1,362.0
September	5.3	1,888.0	1,319.5
October	913.4	744.1	1,528.6
November	2,584.4	351.3	1,504.2
December	4,545.6	290.9	1,554.4
Annual	23,632.5	11,039.9	17,447.8

9.3 Energy Costing

The purpose of this section is to provide the reader with some further insight into the methods employed in developing energy costs in the economic analysis of the HAHP-ICES concept. The space-conditioning loads, upon which the metered energy requirements are based, are provided in Section 9.2.

9.3.1 Base-Case Economic Analysis

In the base-case analysis of the HAHP-ICES concept, the residential community members' annual energy costs with a conventional system were based on the general service gas rates of the East Ohio Gas Company. For the office building, conventional HVAC energy costing was based on the large commercial rate schedule of the Cleveland Electric Illuminating Company. The cost of energy for the HAHP-ICES thermal utility was determined using the large volume general service gas rates and large commercial electric rates of the aforementioned companies. These rate schedules are presented in Tables 9.28 and 9.29.

Table 9.28. THE EAST OHIO GAS COMPANY, GENERAL SERVICE AND LARGE VOLUME
GENERAL SERVICE RATES (Gas Rates)

For Use With Conventional Residential

First 1,000 ft ³ each month	\$4.127
Next 4,000 ft ³ each month	\$2.176/1000 ft ³
All Over 5,000 ft ³ each month	\$2.047/1000 ft ³
Minimum Cost/Month	\$4.13

For HAHP-ICES Case

First 100,000 ft ³ each month	\$2.068/1000 ft ³
Next 900,000 ft ³ each month	\$2.018/1000 ft ³
Next 2,000,000 ft ³ each month	\$1.964/1000 ft ³
Next 2,000,000 ft ³ each month	\$1.904/1000 ft ³
(Plus \$22.00 service charge each month)	

Table 9.29. CLEVELAND ELECTRIC ILLUMINATING CO. LARGE COMMERCIAL RATE
(Electric Rates)

Summer (June through October)			
<u>Demand</u>		<u>Kilowatt Hour</u>	
First 50 kW	\$3.76/kW	First 40,000 kWh	2.39¢/kWh
Excess Over 50 kW	\$2.70/kW	Next 60,000 kWh	1.88¢/kWh
		Excess Over 100,000 kWh	1.28¢/kWh
Winter (November through May)			
<u>Demand</u>		<u>Kilowatt Hour</u>	
First 50 kW	\$3.60/kW	First 40,000 kWh	2.14¢/kWh
Excess Over 50 kW	\$2.55/kW	Next 60,000 kWh	1.63¢/kWh
		Excess Over 100,000 kWh	1.18¢/kWh

9.3.2 Site-Specific Analysis

In the site-specific analysis, the cost of the energy for the various community members that was displaced by the HAHP-ICES thermal utility was based on gas usage, electrical usage, or both. The utility rates employed in this analysis were obtained from the Peoples Natural Gas Company of Pennsylvania and the Duquesne Light Company of Pittsburgh. Because the various community members used different forms and volumes of energy in meeting their respective space-conditioning requirements, the following listing will clarify the assumptions.

- Townhouse and Low-Rise Residential Components: The cost of conventional HVAC energy was based upon gas usage using the residential gas rates.
- High-Rise and Retail Component: These components use both gas and electricity in a conventional application. Commercial gas rates and general service large electric rates are appropriate with respect to the quantities of energy involved.
- Office Component: This component is assumed to use electricity in a conventional application, purchased at the general service large rates.

For the HAHP-ICES application, the central plant purchased gas at the small volume industrial rates and electricity at the general service large rates in meeting the space-conditioning needs of the community. The actual rate schedules for each classification of service appear in Tables 9.30 and 9.31.

Table 9.30. THE PEOPLES NATURAL GAS COMPANY (Pennsylvania),
GAS SERVICE BILLING RATES

Rates Applicable to Townhouse and Low-Rise Residential Components (Conventional)

Customer Charge Per Month	\$ 4.2102
Commodity Charge Per 1000 ft ³	\$ 2.3827

Rates Applicable to High-Rise and Retail Components (Conventional)

Customer Charge Per Month	\$ 7.6933
Commodity Charge Per 1000 ft ³	\$ 2.5768

Rates Applicable to HAHP-ICES Thermal Utility

Customer Charge Per Month	\$16.2552
Commodity Charge per 1000 ft ³	\$ 2.3668

Table 9.31. DUQUESNE LIGHT COMPANY (Pittsburgh, Pennsylvania),
GENERAL SERVICE LARGE (Electric Rates)

Capacity Charge

First 300 kW or Less of Demand	\$1,700
Next 700 kW of Demand at	\$4.11/kW
Additional kW of Demand at	\$3.74/kW

Energy Charge

First 301,000 kWh Plus 80 kWh per kW of Demand at	2.09¢/kWh
Additional kWh at	2.03¢/kWh

Because of the variety of community members in this analysis, as a convenience to the reader, Table 9.32 summarizes the energy costs displaced by the HAHP-ICES thermal utility, and Table 9.33 summarizes the cost of the energy consumed by the central plant in providing the space-conditioning needs of the community.

Table 9.32. ANNUAL COST OF ENERGY CONSUMED BY THE HAHF-ICES
CENTRAL PLANT ON A METERED BASIS (SITE-SPECIFIC CASE)

	Number Of Turbines				
	<u>0.</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Quantity of Gas, 10^6 BTU	52,528	51,238	51,633	50,774	50,396
Compensatory Gas (Distribution Losses)	2,091	2,091	2,091	2,091	2,091
Total Annual Gas, 10^6 BTU	54,619	53,329	53,724	52,865	52,487
Total Cost of Annual Gas, \$	126,869	123,873	124,788	122,793	121,913
Quantity of Electricity, 10^6 BTU	3,095	1,970	1,484	1,152	900
Cost of Electricity, \$	55,778	49,883	44,932	40,496	36,517
Total Annual Energy, 10^6 BTU	57,714	55,299	55,208	54,017	53,387
Total Cost of Annual Energy	182,647	173,756	169,720	163,289	158,430

Table 9.33. ANNUAL COST OF ENERGY DISPLACED BY HAHP-ICES ON A METERED BASIS**

<u>Component</u>	<u>Quantity of Gas, 10⁶ Btu</u>	<u>Cost of Gas, \$</u>	<u>Quantity of Electricity, 10⁶ Btu</u>	<u>Cost of Electricity, \$</u>	<u>Total Annual Energy, 10⁶ Btu</u>	<u>Total Cost of Annual Energy, \$</u>
Office	--		3,494	36,485	3,494	36,485
Retail	6,755	17,177	654	12,990	7,409	30,167
High-Rise*	33,642	85,188	675	29,112	34,317	114,300
Low-Rise	10,268	24,008	--	--	10,268	24,008
Townhouse	4,408	10,337	--	--	4,408	10,337
Total	55,073	136,710	4,823	78,587	59,896	215,297

* Single metering was selected for the high-rise component for establishing conventional energy cost. Separate metering would result in a higher displaced energy cost due to minimum charges per meter.

** Site-specific community.

9.4 System Costing

The purpose of this section is to present the bases for the equipment costs shown in Section 4 (Economics). These costs were compiled by IGT with the assistance of various project team members and a consulting firm in accordance with their individual fields of expertise. Gamze-Korobkin-Caloger, Inc. provided the HVAC equipment requirements and costing information for residential and retail applications throughout this study. R.G. Fleischman Company (Consulting Engineers) supplied requirements and cost data for office space conditioning equipment. Mechanical Technology Incorporated furnished operational and cost data for the HAHP-ICES central plant.

The detailed bases for the equipment and operating and maintenance costs used in the base-case analysis are presented in Tables 9.34 and 9.35. Tables 9.36 through 9.41 present the bases for equipment and operating and maintenance costs used in the economic analysis of the site-specific application of the HAHP-ICES concept: Summary tables appear when appropriate.

The installed cost of the thermal distribution system was estimated at \$45,000 for the base case and \$385,000 for the site-specific case. Although noted here, the complete description of the thermal distribution system and the derivation of the costs assumed are presented in Section 9.6.5.

9.4.1 References Cited

1. Fleischman, R., Fleischman Co., Consulting Engineers, Verona, Pa., private communication, January 1979.
2. Malick, N. Gamze-Korobkin-Caloger, Inc., Chicago, Ill., private communication, February 1979.
3. Burton, D., Mechanical Technology, Inc., Latham, New York, private communication, March 1979.

Table 9.34. BASIS FOR CAPITAL COSTS ASSUMED IN BASE CASE
(Residential and Office)

<u>Residential</u> (24-Apartment Building)	
<u>Equipment</u>	<u>Installed Cost,² Early 1979 \$</u>
<u>Conventional</u>	
24 Gas-Fired Water Heaters, 40 gal	7,450
24 Gas-Fired Furnaces	12,600
24 Split-System Air Conditioners	25,250
Piping Gas	5,650
Piping Flue	8,200
Ductwork	25,250
	<u>84,400</u>
<u>HAHP-ICES</u>	
Base-Board Radiators (27 feet/apartment)	11,100
Piping Hot Water	8,720
Controls/Wiring/Pumps/Valves	2,950
Through-the-Wall Air Conditioners (2/apartment)	28,300
Central Domestic Hot Water System	16,700
ICES Tie-In	600
	<u>68,370</u>
<u>Office</u> (Equipment Which Would be Removed From Office Building)	
<u>Equipment</u>	<u>Installed Cost.^{*1} Early 1979 \$</u>
Chiller, 146 tons	51,350
Boiler, 330 kW	10,900
Cooling Tower, 2.25 X 10 ⁶ Btu/hr	8,621
Storage Tank, 10,000 gal Fiberglass with insulation	10,200
Condenser Water Pump	1,538
Chilled Water Pump	1,538
Hot-Water Pump	1,990
Reduction in Electric Service Entrance	13,260
	<u>99,397</u>

* Material cost times 170% = installed cost. Material costs are from Reference 1.

Table 9.35. BASIS FOR CAPITAL COSTS ASSUMED IN BASE CASE,
HAHP-ICES CENTRAL PLANT

<u>Equipment</u>	<u>Installed Cost,^{*1,3} Early 1979 \$</u>
Primary Boiler, 1.5×10^6 Btu/hr input	17,000
Regenerator	4,250
Turbine, 90 hp	22,100
Turbine Condenser	5,734
Gear Set and Clutch	4,675
Auxiliary Boiler, 2.5×10^6 Btu/hr input	14,875
Auxiliary Condenser	8,840
Compressor C1, 16 hp	544
Condenser C1	2,125
Air Source Evaporator With Fan	1,360
Compressor C2, 80 hp	2,380
Condenser C2	12,750
Evaporator C2	8,500
Motor/Generator, 126 hp	2,145
Compressor C3, 126 hp	4,250
Condenser C3	13,600
Evaporator C3	13,600
Cooling Tower, 3×10^6 Btu/hr	8,500
Controls and Valving	13,600
Chilled Water Pump (Office)	1,538 ²
Hot-Water Pump (Office)	1,900 ²
Condenser Water Pump	1,538 ²
Hot-Water Pump (Residential)	1,700 ^{**}
Feedwater Pumps	500
Electric Service Entrance	4,000 ^{**}
Total	172,444

* Material cost times 170% = installed cost. Material costs are from References 1 and 3.

** IGT estimate.

Table 9.36, Part 1. COMPONENT COSTS — CENTRAL PLANT

A. Cost of turbine with outside air source heat pumping capability; unit not equipped with generator.

<u>Equipment Item</u>	<u>Installed Cost, Early 1979 dollars</u>
Primary Boiler (1.5 X 10 ⁶ Btu/hr input)	17,000
Regenerator	4,250
Turbine, 90 hp	22,100
Turbine Condenser	5,734
Gear Set and Clutch	4,675
Compressor C1, 16 hp	544
Condenser C1	2,125
Air Source Evaporator, with fan	1,360
Compressor C2, 80 hp	2,380
Condenser C2	12,750
Evaporator C2	8,500
Feedwater Pump	500
Condenser Water Pump	1,538
Cooling Tower, refrigerant condenser	4,765
<u>Cooling Tower, Turbine Condenser</u>	<u>3,734</u>
Total Cost of — Turbine with outside air source heat pumping capability	91,955

B. Cost of turbine equipped with generator; no outside air source heat pumping capability.

<u>Equipment Item</u>	<u>Installed Cost, Early 1979 dollars</u>
Turbine with outside air source capability	91,955
Less: Compressor C1	- 544
Air Source Evaporator, with fan	-2,125
Condenser C1	<u>-1,360</u>
Subtotal	87,926
Add: 80 hp Generator	<u>1,633</u>
Total Cost of — Turbine with generator; no outside air source heat pumping capability	89,559

Table 9.36, Part 2. COMPONENT COSTS — CENTRAL PLANT

<u>Equipment Item</u>	<u>Installed Cost, Early 1979 Dollars</u>
C. Valves and Controls (η = number of turbines)	$13,600 + (\eta - 1)(2000)$
D. Auxiliary Primary Boiler Condenser*	$6000 (\eta - 1)$
E. Chilled and Hot Water Pumps — Office	6,000
F. Chilled and Hot Water Pumps — High-Rise	9,500
G. Chilled or Hot Water Pump — Retail	3,400
H. Hot Water Pump — Low-Rise and Townhouse	2,200
I. Auxiliary Boiler	$(14,875) \left[\frac{\text{Boiler Input} - 10^6 \text{ Btu/hr}}{2.5} \right]^{.8}$
J. Auxiliary Condenser	$(3,840) \left[\frac{\text{Boiler Input} - 10^6 \text{ Btu/hr}}{2.5} \right]^{.8}$
K. Auxiliary Electric Centrifugal Chiller and Cooling Tower	$(89,220) \left[\frac{\text{Capacity} (10^6 \text{ Btu})}{2.4} \right]^{.88}$ $5,833/10^6 \text{ Btu of Capacity}$
L. Absorption Chiller and Cooling Tower**	$(293,300) \left[\frac{\text{Capacity} (10^6 \text{ Btu})}{9.6} \right]^{.79}$ $5,833/10^6 \text{ Btu of Capacity}$
M. Electric Service Entrance	$2500 + \left[\frac{1700 \times \text{Auxiliary Electric Centrifugal Chiller Capacity} (10^6 \text{ Btu})}{83.33} \right]$
N. HAHP-ICES Central Plant Building (η = number of turbines)	$(35)(360)(\eta + 2)$ $[(N \times 360) + (\text{Absorption Chiller Capacity} - 10^6 \text{ Btu} \times 184)$ $+ (\text{Auxiliary Electric Chiller Capacity} - 10^6 \text{ Btu} \times 62.5)$ $+ (\text{Primary Boiler Capacity} - 10^6 \text{ Btu} \times 56.5)$ $+ (\text{Auxiliary Boiler Capacity} - 10^6 \text{ Btu} \times 63.7) + 300^{\dagger}] 35$

* For utilization of primary boilers in a supplementary heat only mode.

** Absorption chiller (single effect) is driven by turbine exhaust during cooling season. Applicable only where used in the central plant system.

[†] The 300 ft² addition is to compensate for required office space and controls.

Table 9.37, Part 1. CONVENTIONAL AND HAHP-ICES HVAC COMPONENT COSTS^a

<u>Building Type/System Type</u>	<u>Component</u>	<u>Component Cost</u>
Townhouse (42 Units)/ Conventional	42 Gas-fired furnaces	20,286
	42 Gas-fired water heaters	14,973
	42 Split system air conditioners	40,572
	Gas piping	12,075
	Flue piping	24,150
	Ductwork	72,450
		<u>184,506</u>
Townhouse (42 Units)/ HAHP-ICES ^b	Baseboard radiators	41,538
	42 Water heaters with heat exchanger, no burner	14,973
	126 Thru-the-wall air conditioners (3 per townhouse)	85,491
	Piping, fitting,s valves, controls, wiring - including ICES	31,395
		<u>173,397</u>
Low-Rise (120 Units)/ Conventional	120 Gas-fired furnaces	63,000
	120 Gas-fired water heaters	37,200
	120 Split system air conditioners	126,240
	Gas piping	28,200
	Flue piping	41,040
	Ductwork	126,240
		<u>421,920</u>
Low-Rise (120 Units)/ HAHP-ICES ^b	Baseboard radiators	55,500
	Hot water piping for space heating	43,600
	Thru-the-wall air conditioners (2 per unit)	141,500
	Central domestic hot water system, with heat exchanger	83,500
	Controls/wiring/valves	14,750
	ICES interface	3,000
		<u>341,850</u>
High-Rise (520 Units in five buildings)/ Conventional	Fan coils (1 per apartment)	661,300
	Ductwork	431,300
	Piping, space heating or cooling (includes fittings, valves, pumps, etc.)	230,000
	Central domestic hot water system	189,800
	Piping, domestic hot water	143,800
	Miscellaneous (wiring, controls, etc.)	40,300
	10 - 35 hp Balers (2 per building)	86,300
	Flue piping	57,500
	Gas piping	57,500
	5 - 125 ton centrifugal chillers	
	@ \$542/ton, including cooling tower	<u>389,275</u>
		<u>2,287,075</u>

Table 9.37, Part 2. CONVENTIONAL AND HAHP-ICES HVAC COMPONENT COSTS^a

<u>Building Type/System Type</u>	<u>Component</u>	<u>Component Cost</u>
High-Rise (520 Units in five buildings)/ HAHP-ICES ^c	Fan Coils (1 per apartment)	661,250
	Ductwork	431,250
	2-pipe system (for space heating or cooling; including fittings, valves, etc.)	230,000
	Central domestic hot water system with heat exchanger	201,250
	Piping domestic hot water	143,750
	Miscellaneous (wiring, controls, etc.)	40,250
		<u>1,707,750</u>
Retail Store (135,000 ft ²)/ Conventional - Variable-Air-Volume	Chiller/boiler @ \$2.30/ft ²	310,500
	Ductwork @ \$2.30/ft ²	310,500
	Air handling equipment, controls, electric service entrance, @ \$2.30/ft ²	<u>310,500</u>
		931,500
Retail Store/HAHP-ICES ^d	Ductwork @ \$2.30/ft ²	310,500
	Air handling equipment, controls, ICES interface, etc., @ \$3.11/ft ²	<u>419,175</u>
		729,675
Office (124,000 ft ²)/ Conventional ^e	Chiller, 310 tons @ \$420/ton	130,200
	Boiler, 2 - 330 kW	22,900
	Cooling Tower	21,700
	Storage tank, 20,000 gal fiberglass with insulation	18,000
	Condenser water pump	3,100
	Chilled water pump	3,100
	Hot water pump	4,000
	Reduction in electric service entrance	<u>26,500</u>
		229,500

^a Installed cost, early 1979 dollars. Includes 15% contractor's fee.

^b ICES supplies domestic hot water in the cooling and heating season, with a 2-pipe system from central plant. Central plant does not supply cooling.

^c ICES supplies heating and cooling from central plant; 4-pipe system from central plant also provides domestic hot water during cooling as well as heating season.

^d ICES supplies heating and cooling with a 2-pipe system from central plant.

^e Only includes cost of equipment that would be displaced by ICES. ICES supplies heating and cooling with a 4-pipe system from central plant.

Table 9.38. OPERATING AND MAINTENANCE COSTS

A. Central Plant

1. Turbine driven chiller	
1st 10 years	\$40/ton/yr
2nd 10 years	\$50/ton/yr
2. Absorption chiller	
1st 10 years	\$40/ton/yr
2nd 10 years	\$50/ton/yr
3. Electric driven centrifugal chiller	
1st 10 years	\$40/ton/yr
2nd 10 years	\$50/ton/yr
4. Each turbine and primary boiler	\$1,000/yr
5. Pumps *	
1st 10 years	\$1,000/yr
2nd 10 years	\$1,200/yr
6. Building	
1st 10 years	\$2,000/yr
2nd 10 years	\$2,300/yr

The above costs include the salary of a single operator. However, we estimate two operators would be required. Thus, an additional \$20,000/yr was added to the operating costs used in the analysis.

B. Low-rise (five buildings)	\$6,200/yr	Decrease
C. Townhouse (42 units)	\$2,170/yr	Decrease
D. High-rise (five buildings, 125 tons/building)		
1st 10 years	\$25,000/yr	Decrease
2nd 10 years	\$30,250/yr	Decrease
E. Office		
1st 10 years	\$12,400/yr	Decrease
2nd 10 years	\$15,500/yr	Decrease
F. Retail Store (330 tons)		
1st 10 years	\$13,200/yr	Decrease
2nd 10 years	\$16,500/yr	Decrease

* Circulation pumps for distribution system.

Table 9.39. SUMMARY OF CONVENTIONAL AND HAHP-ICES HVAC SYSTEM COSTS

Building Type	System Type		Savings in HVAC Component Costs Attributable to installation of HAHP-ICES
	Conventional	HAHP-ICES	
Townhouse (42 Units)	184,506	173,397 ^a	11,109
High-Rise (520 Units)	2,287,075	1,707,750 ^b	579,325
Low-Rise (120 Units)	421,920	341,850 ^a	80,070
Retail Store (135,000 ft ²)	931,500	729,675 ^c	201,825
Office (124,000 ft ²) ^d			<u>229,500</u>
		Total	1,101,829

^a ICES supplies domestic hot water in cooling as well as heating season; 2-pipe system from central plant. Central plant does not supply cooling.

^b ICES supplies heating and cooling from central plant with a 4-pipe system from central plant that also provides domestic hot water during cooling and heating season.

^c ICES supplies heating and cooling from central plant with a 2-pipe system from central plant.

^d ICES supplies heating and cooling from central plant with a 6-pipe system from central plant that also provides domestic hot water during cooling and heating season.

Table 9.40. COSTS ASSUMED IN THE ECONOMIC ANALYSIS OF THE SITE-SPECIFIC CASE

<u>Building Type</u>	<u>Decrease in Building Cost*</u>	<u>Yearly Decrease Annual O&M**</u>		<u>Annual Energy Cost With a Conventional System†</u>
		<u>First 10 Years</u>	<u>Second 10 Years</u>	
Townhouse Apartment (42 Units)	\$11,109	\$2,170	--	\$10,337
High-Rise Residential (520 Units)	\$579,325	\$25,000	\$30,250	\$114,300
Low-Rise Residential (120 Units)	\$80,070	\$6,200	--	\$24,008
Office (124,000 ft ²)	\$229,500	\$12,400	\$15,500	\$36,485
Retail (135,000 ft ²)	\$201,825	\$13,200	\$16,500	\$30,167

* Initial reduction in required HVAC equipment resulting from implementation of HAHP-ICES concept.

** Annual reduction in operating and maintenance expenses resulting from implementation of HAHP-ICES concept.

† Annual reduction in energy costs for conventional heating and/or cooling, displaced as a result of the implementation of HAHP-ICES concept.

Table 9.41. COSTS ASSUMED FOR HAHP-ICES THERMAL UTILITY
IN THE SITE-SPECIFIC CASE

<u>Number of Turbines</u>	<u>Installed Costs</u>	<u>Annual Operating and Maintenance (First 10 Yrs)</u>	<u>Annual Operating and Maintenance (Second 10 Yrs)</u>	<u>Energy Costs*</u>
0	\$655,244	\$57,319	\$66,339	\$182,647
1	\$724,855	\$58,329	\$67,912	\$173,756
2	\$793,137	\$59,328	\$69,411	\$169,720
3	\$859,134	\$60,333	\$70,917	\$163,289
4	\$926,456	\$61,334	\$72,419	\$158,430

* Includes \$4,850 for distribution thermal losses.

9.5 Description of the Equations Employed in the Economic Model

This section presents the specific mathematical equations employed in the computer model that was used to evaluate the economic feasibility of the HAHP-ICES concept. Rather than offer the computer program itself, with the idiosyncrasies of various hardware and software considerations that are unique to an individual computer system, a narrative description of each term of Equation A in Table 9.42 and Equation B in Table 9.43 is provided.

9.5.1 Equations Used in the Model Relative to the Community Members

$$PV(\text{Heating \& Cooling Charges}) = PV(\text{Revenues}) - PV(\text{Interest}) - PV(\text{Operating \& Maintenance}) - PV(\text{Insurance}) \\ - PV(\text{Property Tax}) + \frac{PV(\text{Equity Investment})}{(T-1)} + \frac{PV(\text{Amortization})}{(T-1)} - \frac{T \times PV(\text{Depreciation})}{(T-1)}$$

- PV(Revenues): The energy savings resulting from the implementation of the HAHP-ICES are treated as revenues in this model. When energy costs are assumed to be static (simulating the effect of general inflation impacting equally and simultaneously on all costs), the displaced energy costs are multiplied by the time-value factor for the present value of an annuity.

$$PV(\text{Revenues}) = \text{Energy} \times \frac{(1 + \text{Disc Rate})^{20} - 1}{\text{Disc Rate} (1 + \text{Disc Rate})^{20}}$$

Where -

Energy is the annual cost of the energy displaced by the HAHP-ICES, Disc Rate is the appropriate discount rate, and the exponent (20) is the assumed project life. When energy costs were assumed to escalate annually at some level above the rate of general inflation, the following formulae are used:

$$PV(\text{Revenues}) = \left[\text{Displaced Electricity} \times \frac{(1 + \text{Con Rate}_{\text{elec}})^{20} - 1}{\text{Con Rate}_{\text{elec}} \times (1 + \text{Con Rate}_{\text{elec}})^{20}} \right] \\ + \left[\text{Displaced Gas} \times \frac{(1 + \text{Con Rate}_{\text{gas}})^{20} - 1}{\text{Con Rate}_{\text{gas}} \times (1 + \text{Con Rate}_{\text{gas}})^{20}} \right]$$

Where -

$$\text{Con Rate}_{\text{elec}} = \frac{\text{Disc Rate} - \text{Escal}_{\text{elec}}}{1 + \text{Escal}_{\text{elec}}}$$

$$\text{Con Rate}_{\text{gas}} = \frac{\text{Disc Rate} - \text{Escal}_{\text{gas}}}{1 + \text{Escal}_{\text{gas}}}$$

Energy costs are treated as a geometric progression, increasing annually by a fixed rate of change over the life of the project. Because the implementation of the HAHP-ICES may result in the displaced usage of gas, electricity or both, depending upon the community member; and the rates of escalation for gas and electricity may differ, separate "convenience rates" (Con Rate) must be established.

Table 9.42. MATHEMATICAL DERIVATION OF ECONOMIC MODEL AS IT RELATES TO
COMMUNITY MEMBERS SERVED BY THE HAHP-ICES THERMAL UTILITY*

$$PV(\text{Equity Investment})^{**} = (1 - T)[PV(\text{Revenues}) - PV(\text{Costs})] + PV(\text{Depreciation}) - PV(\text{Amortization})$$

Where T is the effective tax rate.

$$PV(\text{Costs}) = PV(\text{Heating \& Cooling Charges}) + PV(\text{Interest}) + PV(\text{Operating \& Maintenance}) + PV(\text{Insurance}) \\ + PV(\text{Property Tax}) + PV(\text{Depreciation})$$

So, substituting the second equation for PV(Costs) in the first equation:

$$PV(\text{Equity Investment}) = (1 - T)[PV(\text{Revenues}) - PV(\text{Heating \& Cooling Charges}) - PV(\text{Interest}) \\ - PV(\text{Operating \& Maintenance}) - PV(\text{Insurance}) \\ + PV(\text{Property Tax}) - PV(\text{Depreciation})] + PV(\text{Depreciation}) - PV(\text{Amortization})$$

Solving for the PV(Heating & Cooling Charges),

$$PV(\text{Heating \& Cooling Charges}) = PV(\text{Revenues}) - PV(\text{Interest}) - PV(\text{Operating \& Maintenance}) - PV(\text{Insurance}) \\ - PV(\text{Property Tax}) + \frac{PV(\text{Equity Investment})}{(T - 1)} + \frac{PV(\text{Amortization})}{(T - 1)} - \frac{T \times PV(\text{Depreciation})}{(T - 1)} \quad (A)$$

Assumptions:

1. Energy savings resulting from the implementation of the HAHP-ICES are treated as the Revenues of the community members served by the HAHP-ICES thermal utility.
2. The tax rate chosen reflects tax preference items.
3. Operating and maintenance costs are treated as differential costs with respect to a conventional system.

* See Table 4.3 for the definition of terms used in this section.

** This assumes that off-the-shelf components are installed by the beginning of the first year of operation with all construction interest and insurance included, i.e., we are assuming PV(Equity Investment) is equal to the actual Equity Investment.

Table 9.43. MATHEMATICAL DERIVATION OF ECONOMIC MODEL AS IT RELATES TO HAHP-ICES THERMAL UTILITY

$$PV(\text{Equity Investment}) = PV(\text{Revenues}) - PV(\text{Costs}) + PV(\text{Depreciation}) - PV(\text{Amortization})$$

Where:

$$PV(\text{Costs}) = PV(\text{Distribution System}) + PV(\text{Interest}) + PV(\text{Operating \& Maintenance}) + PV(\text{Insurance}) \\ + PV(\text{Property Taxes}) + PV(\text{Depreciation}) + PV(\text{Energy Costs})$$

$$PV(\text{Revenues}) = \sum PV_{\text{ATEC}}$$

The present value of the annual HAHP-ICES thermal utility's revenue is equal to the summation of the annual thermal energy charges of the community it serves.

Thus on a pre-tax basis, and substituting the second equation for PV(Costs) in the first equation:

$$PV(\text{Equity Investment}) = [PV(\text{Revenues}) - PV(\text{Distribution System}) - PV(\text{Interest}) - PV(\text{Energy Costs}) \\ - PV(\text{Operating \& Maintenance}) - PV(\text{Insurance}) - PV(\text{Property Tax}) - PV(\text{Depreciation})] \\ + PV(\text{Depreciation}) - PV(\text{Amortization})$$

Solving for the PV(distribution):

$$PV(\text{Distribution System}) = PV(\text{Revenues}) - PV(\text{Interest}) - PV(\text{Energy Costs}) - PV(\text{Operating \& Maintenance}) \\ - PV(\text{Insurance}) - PV(\text{Property Tax}) - PV(\text{Equity Investment}) - PV(\text{Amortization}) \quad (B)$$

Assumptions:

1. The HAHP-ICES thermal utility's revenues are equal to the present value of the acceptable annual thermal energy charges assessed from the community it serves.
2. The cost of energy (gas and electricity) to the utility and the operating and maintenance expenditures are treated as actual costs, not on a differential basis with a conventional system.
3. The calculations are on a pre-tax basis.

A "convenience rate" is one which provides for both a constant rate of change and the discounting for both time-value of money. The discount rate is that which is appropriate for the community member being evaluated.

- PV(Interest) and PV(Amortization): These values are calculated and discounted for each year of the mortgage life. The annual mortgage payment is computed by multiplying that portion of the capital requirements which is to be financed through debt by the appropriate amortization factor.

$$\text{Annual Payment} = \text{Debt} \times \left(\frac{\text{Int}_{\text{Mort}} \times (1 + \text{Int}_{\text{Mort}})^{20}}{(1 + \text{Int}_{\text{Mort}})^{20} - 1} \right)$$

Where —

Int_{Mort} is the annual mortgage interest rate and the exponent (20) is the assumed life of the loan.

Once the annual payment is obtained, the yearly interest payment is computed by multiplying the outstanding balance of the loan by the mortgage interest rate. The yearly principal portion of the annual payment is simply the annual payment less the yearly interest payment. The outstanding balance of the loan is then adjusted to reflect the payment of principal for that year and the above process is repeated for each year (N) of the mortgage life (20). The following equations reiterate this process.

$$\text{Interest Payment}_N = \text{Balance}_{\text{Loan}} \times \text{Int}_{\text{Mort}}$$

$$\text{Principal Portion}_N = \text{Payment}_{\text{Annual}} - \text{Interest Payment}_N$$

$$\text{Balance}_{\text{Loan}} = \text{Balance}_{\text{Loan}} - \text{Principal Portion}_N$$

The annual interest and principal payments are discounted yearly over the life of the loan (20 years).

Thus:

$$\text{PV(Interest)} = \sum_{N=1}^{20} \frac{\text{Interest Payment}_N}{(1 + \text{Disc Rate})^N}$$

$$\text{PV(Amortization)} = \sum_{N=1}^{20} \frac{\text{Principal Portion}_N}{(1 + \text{Disc Rate})^N}$$

Where —

N is the year in the mortgage life under evaluation.

- PV(Operating and Maintenance): The annual operating and maintenance charges enter the model as data. There may or may not be an incrementation of this amount in the tenth year of operation. With this in mind, the amounts are discounted accordingly.

$$\text{Temp} = \frac{\text{O\&M}_{(10-20)} \times [(1 + \text{Disc Rate})^{10} - 1]}{\text{Disc Rate} (1 + \text{Disc Rate})^{10}}$$

The annual O&M expenses for years 10-20 are discounted back to the tenth year and assigned a temporary variable name. The value of "Temp" must then be discounted back to the first year of the of system operation (base year).

$$\text{PV}(\text{O\&M}_{10-20}) = \frac{\text{Temp} \times 1}{(1 + \text{Disc Rate})^{10}}$$

The O&M charges for the first ten years are discounted back to the base year in the following manner:

$$\text{PV}(\text{O\&M}_{1-10}) = \left[\frac{\text{O\&M}_{(1-10)} \times [(1 + \text{Disc Rate})^{10} - 1]}{\text{Disc Rate} (1 + \text{Disc Rate})^{10}} \right]$$

The two individual values are summed to obtain the present value of operating and maintenance expenses for the life of the project.

$$\text{PV(Operating and Maintenance)} = \text{PV}(\text{O\&M}_{1-10}) + \text{PV}(\text{O\&M}_{10-20})$$

- PV(Insurance) and PV(Property Taxes): The annual expenses for insurance and property taxes were assumed to be equal to 1% of the total required investment, and calculated in the following manner.

$$\text{PV(Insurance)} = \text{PV(Property Taxes)} = \frac{(\text{Capital Required} \times .01) \times [(1 + \text{Disc Rate})^{20} - 1]}{\text{Disc Rate} (1 + \text{Disc Rate})^{20}}$$

- PV(Equity): Because we are assuming that off-the-shelf components are installed by the beginning of the first year of operation with all construction interest and insurance included,

$$\therefore \text{PV(Equity)} = \text{Equity Investment}$$

- PV(Depreciation): Double declining balance depreciation was selected for use in this model. The community members were assumed to elect additional first-year depreciation which is known as bonus depreciation. In addition to the regular depreciation deduction which can be taken in the first year, taxpayers can elect an initial deduction equal to 20% of the first \$10,000 of investment, up to a maximum of \$2,000 on qualified property.*

* Tangible personal property with a useful life of at least 6 years.

The basis for depreciation on that property is reduced by the "bonus," and normal depreciation for that year is calculated in the usual manner. The "asset value" in our model is equal to the differential cost of HAHP-ICES equipment with respect to a conventional HVAC system (the capital requirements of our system).

The annual depreciation expenses are calculated in the following manner:

$$\text{Dep Basis}_1 = \text{Asset Value} - 2000$$

$$\text{Dep}_1 = (\text{Dep Basis}_1 \times \frac{2}{20}) + 2000$$

$$\text{Dep Basis}_2 = (\text{Dep Basis}_1 - \text{Dep}_1) + 2000$$

$$\text{Dep}_{N-2, 10} = \text{Dep Basis}_N \times .1$$

} Nine Iterations

$$\text{Dep Basis}_{N+1} = \text{Dep Basis}_N - \text{Dep}_N$$

Where the basis for depreciation of the asset is reduced by the maximum allowable "bonus" (\$2000), and DDB* depreciation is calculated [with the depreciation rate equal to the declining balance rate, 2, over the asset life (in years) 20]. The depreciable basis for Year 2 is adjusted (by \$2000) to prevent a "double accounting" of the "bonus" (i.e., the asset value was previously reduced by the bonus to arrive at the depreciable basis for normal depreciation for Year 1; the bonus also appears in the total depreciation for Year 1, Dep_1).

Beginning in Year 11, we switch from DDB depreciation to straight-line depreciation, and use this method over the remaining life.

$$\text{Dep}_{N=11 \rightarrow 20} = \text{Dep Basis}_{11} \div 10$$

The depreciation for each of the years 11 through 20 is equal to the depreciable basis in Year 11 divided by the remaining life (10 years).

The annual depreciation expenses are discounted in the following manner:

$$\text{PV}(\text{Depreciation}) + \sum_{N=1}^{20} \frac{\text{Dep}_N}{(1 + \text{Disc Rate})^N}$$

Where -

N = year.

Dep_N = the depreciation for that year

Disc Rate = the appropriate discount rate for the community member in question.

* Double declining balance.

Once the amount and timing of each cost (benefit) has been projected for the system's lifetime, and discounted back to the first year of operation; the terms are combined in the following equation to determine the life-cycle heating and cooling charges applicable to that community member. PV(Heating and Cooling Charges) is then annualized into level payments, to determine the amount each community member can pay (annually) in order to equate their HAHP-ICES' costs with that of a conventional HVAC system.

$$PV(\text{Heating \& Cooling Charges}) = PV(\text{Revenues}) - PV(\text{Interest}) - PV(\text{Operating \& Maintenance}) - PV(\text{Insurance}) - PV(\text{Property Tax}) + \frac{PV(\text{Equity Investment})}{(T-1)} + \frac{PV(\text{Amortization})}{(T-1)} - \frac{T \times PV(\text{Depreciation})}{(T-1)}$$

- $PV(\text{Annual Thermal Energy Charges}) =$

$$PV(\text{Heating and Cooling Charges}) \times \left[\frac{\text{Disc Rate} (1 + \text{Disc Rate})^{20}}{(1 + \text{Disc Rate})^{20} - 1} \right]$$

9.5.2 The Equation Relative to the HAHP-ICES Thermal Utility

The evaluation of the HAHP-ICES concept is based on the present value of the distribution system which is calculated in the following equation:

$$PV(\text{Distribution System}) = PV(\text{Revenues}) - PV(\text{Interest}) - PV(\text{Energy Costs}) - PV(\text{Operating \& Maintenance}) - PV(\text{Insurance}) - PV(\text{Property Tax}) - PV(\text{Equity Investment}) - PV(\text{Amortization})$$

The equation solves for the excess of system resultant revenues over system resultant costs of the HAHP-ICES thermal utility that will be used to defray the life-cycle cost of the distribution system. As before, the description and method of calculating the value of each term will be presented.

- PV(Revenue): The annual revenues of the HAHP-ICES thermal utility are composed of a summation of the annual thermal energy charges for the community members which were calculated in Subsection 9.5.1. The present value of these revenues is calculated by multiplying the annual revenues by the time-value factor for the present value of an annuity.

$$PV(\text{Revenue}) = \sum \text{ATEC} \times \frac{\text{Disc Rate} (1 + \text{Disc Rate})^{20}}{(1 + \text{Disc Rate})^{20} - 1}$$

Where —

$\sum \text{ATEC}$ is the summation of the annual thermal energy charges assessed to each community member, Disc Rate is the rate of return required by the HAHP-ICES thermal utility (15%), and the exponent (20) is the project's life in years.

- PV(Interest) and PV(Amortization): The HAHP-ICES thermal utility is financed through an equal load amortization type loan (straight-line amortization of the principal). The annual principal payments are level throughout the life of the loan and are calculated by multiplying the amount of the loan by the reciprocal of the life of the loan in years (20).

$$\text{Annual Principal Payments} = \text{Debt} \times \frac{1}{20}$$

Because the principal payments are an annuity (level over the life of the loan), they can be discounted by multiplying the calculated value of a single principal payment by the time-value factor for the present value of an annuity.

$$\text{PV (Amortization)} = \text{Annual Principal Payment} \times \left[\frac{\text{Disc Rate} (1 + \text{Disc Rate})^{20}}{(1 + \text{Disc Rate})^{20} - 1} \right]$$

Where —

Disc Rate = the required rate of return on investment
The exponent (20) = the life of the loan in years.

The annual interest payments are not an annuity, and must be calculated by an iterative technique for each year of the life of the loan.

$$\text{Interest Payment}_N = \text{Remaining Balance}_N \times \text{Int Rate}$$

$$\text{Remaining Balance}_N = \text{Remaining Balance}_{N-1} - \text{Annual Principal Payment}_{N-1}$$

Where —

Remaining Balance₁ is the amount of the original loan, and N is the year in the life of the loan (1 through 20) under evaluation.

The annual interest payments are discounted in the following manner:

$$\text{PV(Interest)} = \sum_{N=1}^{20} \frac{\text{Interest Payment}_N}{(1 + \text{Disc Rate})^N}$$

- PV(Energy Costs)
 - PV(Operating and Maintenance)
 - PV(Property Tax)
 - PV(Equity Investment)
- These terms are treated simultaneously because they are calculated in the same manner as in Section 9.5.1 (The Equation Relative to the Community Members). The appropriate discount rate used in the time-value calculations was the return on investment required by the HAHP-ICES thermal utility (15%).

The above terms are combined in the following equation, where the PV(Distribution System) term represents the excess of the system-resultant revenues over the system-resultant costs which is available to defray the life-cycle cost of the distribution system.

$$\text{PV(Distribution System)} = \text{PV(Revenues)} - \text{PV(Interest)} - \text{PV(Energy Costs)} - \text{PV(Operating \& Maintenance)} \\ - \text{PV(Insurance)} - \text{PV(Property Tax)} - \text{PV(Equity Investment)} - \text{PV(Amortization)}$$

9.5.3 Calculation of Site-Specific Cash Flows

Pre and after-tax net cash flow calculations were performed for the site-specific turbine cases based on the following assumptions.

- The HAHP-ICES thermal utility is treated as an independent domestic corporation for tax and accounting purposes. The appropriate tax rates are presented in Table 9.44.
- The thermal distribution system cost of \$385,000 is added to the capital requirements of the HAHP-ICES thermal utility.
- The gas required by the central plant has been adjusted to reflect thermal losses (gains) in supplying heating, cooling, and domestic hot water to the community. As before, the HAHP-ICES will finance 75% of the total cost of the project through debt, 25% through equity. The 2% allowance for "other" annual costs (insurance and property) also pertain to the cost of the distribution system.

The method used for determining after-tax cash flows (in our leveraged situation) is simply the HAHP-ICES thermal utility's revenues less the operating costs (operating and maintenance, insurance, property taxes, and annual energy expense), less the interest on debt, less depreciation to arrive at taxable income. The taxable income is reduced by the appropriate amount of taxes to arrive at the net profit, and the depreciation is added back to arrive at the cash flow. By reducing the cash flow by the principal payment, the net cash flow is obtained. Pre-tax net cash flows differ from after-tax net cash flows simply by the appropriate amount of the tax. The analysis is provided on a pre- and after-tax basis to provide the reader with more complete information for judging the acceptability of this project.

The annual net cash flows were then discounted until their sum was equal to the equity investment, based upon our assumed leveraged position. The discounted cash flow rate of return on the initial equity investment would be, in essence, the maximum ROR given that the thermal utilities revenues are based on annual thermal energy charges that equate the HAHP-ICES cost of service with that of a conventional system. If the owners of the thermal utility would accept a lesser rate of return, then the HAHP-ICES cost of service to community members could be reduced accordingly.

Table 9.45 display a sample five years of after-tax cash flow calculations for a selected case. Note that the zero turbine case was chosen purely for illustrative purposes, the methodology remains the same for each of the other cases.

Table 9.44. GRADUATED CORPORATE FEDERAL INCOME TAX SCHEDULE*

<u>Tax Rate</u>	<u>Basis</u>
17%	Taxable income up to \$25,000
20%	The next \$25,000 of taxable income
30%	The next \$25,000 of taxable income
40%	The next \$25,000 of taxable income
46%	Taxable income over \$100,000

* For tax years beginning in 1979. Source: Publication 6303 - Commerce Clearing House - Master Tax Guide, 1979.

Table 9.45. CASH FLOW CALCULATIONS — 0 TURBINE CASE

Year	<u>1</u>	<u>2</u>	<u>3</u> \$	<u>4</u>	<u>5</u>
Income (Revenue)	489,852.69	489,852.69	489,852.69	489,852.69	489,852.69
- O & M	57,319.00	57,319.00	57,319.00	57,319.00	57,319.00
- Insurance	10,402.44	10,402.44	10,402.44	10,402.44	10,402.44
- Property Tax	10,402.44	10,402.44	10,402.44	10,402.44	10,402.44
- Annual Energy Expense	182,647.00	188,899.99	195,400.43	202,158.72	209,185.66
- Loan Payment - Interest	78,018.30	74,117.38	70,216.47	66,315.56	62,414.64
- Depreciation	<u>104,024.40</u>	<u>93,621.96</u>	<u>84,259.76</u>	<u>75,833.79</u>	<u>68,250.41</u>
Taxable Income	47,039.11	55,089.48	61,852.14	67,420.75	71,878.10
- Income Tax	8,657.82	10,776.84	12,805.64	14,476.22	15,813.43
- Loan Payment - Principal	39,009.15	39,009.15	39,009.15	39,009.15	39,009.15
+ Depreciation	<u>104,024.40</u>	<u>93,621.96</u>	<u>84,259.76</u>	<u>75,833.79</u>	<u>68,250.41</u>
Net Cash Flow	103,396.54	98,925.44	94,297.11	89,769.16	85,305.93

The reader will probably notice that the revenues remain the same over the life of the project even though energy rates are escalating and it has been previously stated that the revenues of the HAHP-ICES thermal utility are predicated on the cost of conventional HVAC system ownership. The HAHP-ICES thermal utility's revenues are based on its annual thermal energy charges to its community membership. These annual charges are developed for each community member based on a differential life-cycle cost comparison between a conventional HVAC and the HAHP-ICES. For each member, the timing and amount of all costs that would not be incurred with the selection of the HAHP-ICES were projected for the system's lifetime. The computation of the present value of this distribution of cash flows collapses that distribution into a single number. For a given interest rate and time origin and a given distribution of cash flows, this number will be unique. The inverse of this operation is not unique. For a given present value, interest rate and time interval, there are an infinite number of equivalent cash flows. Because the annual energy escalations are part of our present values of allowable annual thermal energy charges, annualizing these figures gives a fair and adequate representation of the stream of revenues to the HAHP-ICES thermal utility.

9.6 Expected Performance

9.6.1 Components of the HAHP-ICES Central Plant

Components of the HAHP-ICES central plant consist of the following:

- Mechanical, vapor compression heat-pump unit(s), driven by a gas-fired steam turbine prime mover
- Supplemental low-pressure steam boiler(s)
- Electrically-driven, mechanical vapor compression chiller(s)
- Hot- and chilled-water distribution pumps
- Cooling tower(s).

9.6.2 Operation of the Central Plant

- Heat sources are outside air and/or internal cooling loads.
- The goal is to operate the heat pump portion of the HAHP-ICES central plant in a manner which maximizes the utilization of available refrigerant condenser and turbine condenser heat,
- To minimize rejection of condenser heat, the central plant is operated by a load-following control philosophy.
- Load following to satisfy HVAC loads is accomplished by simultaneously modulating turbine shaftpower output, heat pump condenser output, and the production of electricity. Where more than one heat pump module is used, modules may be brought in and out of service.
- Table 9.46 details the base-case HAHP-ICES central plant control philosophy.
- Table 9.47 details the site-specific case HAHP-ICES central plant control philosophy.

9.6.3 Development of HAHP-ICES Heating and Cooling Performance – Basic Assumptions

The basic assumptions used in the development of the heating and cooling performance are presented below:

- Efficiency of gas production and transmission = 0.95%.
- Efficiency of electricity generation and distribution = 0.2968%.
- Steam generator efficiency = 0.83%.
- Turbine horsepower = 90 hp.
- Mechanical parasitics = 8.04 hp.

Table 9.46. HAHP-ICES CONTROL PHILOSOPHY

- I. General Rule: System follows load so that only in the cooling mode is heat rejected to the cooling tower
- II. Heating mode with ambient temperature less than 30°F*
 - A. Internal heat pumping available
 1. Limit amount of heat pumped to equal office heat load
 - a. If office heat load is greater than internal pumped heat available, supplemental heat comes directly from boiler.
 - b. If office heating load is less than internal pumped heat available, then excess turbine shaft power is available for production of electricity to help satisfy HVAC parasitics, under the restrictions that:
 1. A load exists for the associated turbine heat
 2. The electricity can be consumed on-site for HVAC parasitics
 3. The amount of electricity produced is at least 5 kW
 2. Turbine condenser heat is used to help satisfy the residential heat load
 - a. If turbine condenser heat exceeds residential heating load, turbine shaftpower output is limited such that the sum of pumped heat and turbine condenser heat equals the total office building heat load and the residential heat load
 - b. If turbine condenser heat is less than the residential heat load, additional heat is supplied directly from the boiler.
 3. See Item V
 - B. External heat pump when internal cooling load not available. Follow same operating rules as for internal heat pumping case.
 - C. If heat pumping not available, produce electricity following Rule II, A, 1, b, and meet additional heat load with boiler.
- III. Heating mode with ambient temperature greater than 30°F
 - A. In this mode, pumped heat can be added to the residential heating thermal distribution loop with the limitation that the return water temperature may be increased by only 5°F by refrigerant condenser heat. The upper limit on pumped heat imposed by this constraint is the sum of the office building heat load plus a percentage of the residential heat load. This percentage is 20% at an ambient temperature of 30°F, increasing to 25% at 50°F.
 - B. Overall operation is guided by the same control philosophy as for ambient temperatures less than 30°F.
- IV. Cooling load with ambient temperature greater than 70°F
 - A. Operate turbine driven chiller first. Meet additional cooling load with electrically driven chiller. If cooling load is less than turbine driven chiller maximum output, generate electricity following Rules in II, A, 1, b. In all cases, use turbine condenser heat to meet residential heating load which during cooling season consists of the office and residential domestic hot water load. Refrigerant condenser heat and excess turbine condenser heat is rejected at the the cooling tower.
- V. Cooling load with ambient temperature less than 70°F
 - A. The cooling load remaining above internal heat pumping cooling capacity is met with outside air ventilation up to the limit of the office building's 60,000 CF/min air handlers. Any additional cooling load is met with the turbine driven chiller. Excess refrigerant condenser heat and turbine condenser heat is rejected at the cooling tower.

* Because refrigerant condenser heat is at a relatively low temperature, only office heating loads can be served by pumped heat when ambient temperature is less than 30°F. Office is equipped with fan coils which can utilize lower temperature heat than baseboard units used in residences.

Table 9.47. CONTROL PHILOSOPHY - SITE-SPECIFIC CASE

- I. General Rule: System follows load so that only in the cooling mode is heat rejected to the cooling tower.
- II. Heating Mode*
 - A. If internal heat pumping is available
 1. Use at least one turbine-driven unit in the internal heat pump mode and additional units as necessary up to the total units less one.
 2. Use one turbine to generate electricity for pumping loads
 3. Use any remaining turbine-driven units in external heat pump mode as necessary
 4. Meet additional heat requirements with boilers
 - B. If internal heat pumping is not available
 1. Use one turbine-driven unit in external heat pump mode
 2. Use one turbine to generate electricity for pumping loads
 3. Use remaining turbine-driven units in external heat pump mode as necessary
 4. Meet additional heat requirements with boilers
- III. Cooling Mode
 - A. Use turbine-driven units in cooling mode as necessary
 - B. If all turbines are not in use for cooling, generate electricity for pumping loads
 - C. Meet additional cooling loads with auxiliary cooling units
 - D. If heating load (DHW) is greater than turbine condenser heat available, meet additional heating load with boilers.

* In both internal and external heat pump modes, the limit on total pumped heat usable by the system (assuming source heat or number of turbines do not impose a limit) is equal to:

- at ambient temperature less than 30°F - the office space heating load
- at ambient temperature above 30°F - the office space heating load plus a percentage of the high temperature heating loads. This percentage is 20% at a 30°F ambient, increasing to 25% at 50°F.

- Gear box mechanical efficiency = 0.961%.
- Available horsepower to compressor = $(90 - 8.04)(0.961) = 78.76$ hp.
- Horsepower available after mechanical losses determines compressor size.
- Condenser heat available is reduced by turbine jacket losses of 5% of turbine power output and assumes condenser heat losses of 5%.
- Part load turbine efficiency (base case) =

$$(\text{full load turbine efficiency}) - \left[\frac{(50) \left(1 - \frac{\text{net horsepower}}{78.76} \right)}{100.0} \right]$$

- Part load turbine efficiency (site-specific case) =
(full load efficiency)(Y)

where -

$$Y = A + BX + CX^2$$

X = decimal fraction of net full load (78.76 hp) output

$$A = 0.520$$

$$B = 1.126$$

$$C = -6.641 \times 10^{-1}$$

- Auxiliary boiler efficiency at full and part load (base case) = 0.83%
- Auxiliary boiler efficiency (site-specific case):

<u>Load, %</u>	<u>Auxiliary Boiler Efficiency, %</u>
>100	0.800
100	0.830
90	0.830
80	0.830
70	0.824
60	0.818
50	0.812
40	0.806
30	0.80

9.6.4 Water Delivery Temperature Schedule

A water delivery temperature schedule ensures that heating season loads are satisfied by reasonably-sized terminal equipment; it is also important in the determination of appropriate refrigerant condenser and turbine exhaust temperatures to provide adequate heat transfer. A minimum send-out temperature is also necessary to ensure that domestic hot-water temperature requirements are satisfied.

The water delivery temperature schedule used in both the base and site-specific cases is presented in Figure 9.6. Because the perimeter baseboard terminal units used in the low-rise and townhouse buildings and fan coils in the high-rise and retail buildings require higher water temperatures than the fan coil units used in the office structure, the send-out temperatures are different for the office and residential/retail loads. The heating requirements of the office building are met with heat-pump condenser heat, and supplemented with turbine exhaust heat and direct boiler heat when necessary. Supplemental turbine condenser heat can be supplied by a separate heat exchanger coil in the turbine condenser (not shown in the diagram of the system) or the office thermal distribution loop can be supplemented with hot water from the residential thermal distribution loop. The send-out temperature is 120°F to the office building, and the return temperature is regulated to provide a return temperature of about 100°F.

Residential and retail store heating loads are met by turbine exhaust heat supplemented by direct boiler heat for ambient temperatures below 30°F. Below an ambient temperature of 0°F, the residential send-out temperature is 190°F with a return temperature, at full load, of 165°F. Turbine condenser temperature is 200°F. Send-out temperatures decrease to 140°F at an ambient temperature of 50°F, while return temperatures decrease to 120°F at 50°F and full load. Turbine condensing temperature is maintained at 10°F above send-out temperature. The minimum residential send-out temperature of 140°F is sufficient to provide residential and commercial domestic hot water at 130°F. Above an ambient temperature of 30°F, refrigerant condenser temperature is sufficiently above the residential return temperature so that heat pump output can contribute to meeting the residential heating load if excess heat is available above the office load. In the heat-pump system, return water from residential loads flows first through the refrigerant condenser and then through the turbine condenser to maximize thermodynamic efficiency. The chilled water send-out temperature is 44°F. Chilled water return temperature is 55°F.

9.6.5 Thermal Distribution System

A thermal distribution system is required to supply hot or chilled water to community loads. In the base case, only hot water is distributed to residential loads for space heating and domestic hot water; cooling is supplied by thru-the-wall air conditioners. No distribution system is required to supply hot and chilled water to the office building because the HAHP-ICES is assumed to be located in the equipment room of the office building. In the site-specific case, low-rise and townhouse dwellings receive hot water only; the high-rise apartments and office and retail buildings are supplied with both hot and chilled water to provide year-round space heating, cooling, and domestic hot water.

In the base case there is only two pipes — a send-out and return line for hot water. In the site-specific case, buildings served by hot water have a two-pipe distribution system; buildings supplied with heating and cooling have four pipes, two for hot water and two for chilled water.

The HAHP-ICES thermal distribution system has a variable flow rate pumping scheme. The system matches the flow rate of the thermal distribution system to the thermal loads in order to reduce pumping parasitic loads.

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Figure 9.6. SEND-OUT AND RETURN TEMPERATURES, FAHP-ICES

In both the base and site-specific cases, the distribution system is assumed to be direct buried in a common trench and installed prior to the installation of site improvements such as streets, parking lots, and landscaping. The piping is Schedule 40 steel with polyurethane foam insulation, protected by a tension filament-wound multi-directional fiberglass-reinforced polyester resin outer jacket. Table 9.4.8 shows the insulation thickness and estimated cost by pipe size. The system design assumed an allowed pressure drop of 50 psi (round trip) under peak load conditions for each major system segment. The only exception was in the site-specific case where the total round-trip pressure drop for the thermal distribution system segment serving the low-rise and townhouse dwellings was 100 psi under peak load conditions.

Table 9.4.8. PIPE COST AND INSULATION THICKNESS

[*] Nominal Pipe Size, in.	^{**} Insulation Thickness, in.	Cost of Supply and Return, \$/ft [†]
2	1	11.42
3	1	13.70
4	1	17.56
5	1	21.56
6	1	25.10
8	1.5	40.40
10	1.5	52.17
12	1.5	62.88

* Schedule 40.

** Polyurethane foam.

† Cost is for 2 feet of pipe, one foot of supply and one foot of return. Costs are 1977 dollars updated to 1979 dollars via M&S equipment cost index and include an allowance for critical period job site supervision and freight (Illinois to Maryland).

9.6.5.1 Base-Case Thermal Distribution System

Figure 9.7 shows the distribution network assumed and Table 9.4.9 shows system data by pipe segment and the total estimated system cost. Total distribution system cost for the base-case community was \$45,000

9.6.5.2 Site-Specific Thermal Distribution System

Figure 9.8 shows the distribution system layout assumed for the site-specific case. Table 9.50 shows the thermal distribution system characteristics by pipe segment and the total estimated thermal distribution system cost. Total distribution system cost for the site-specific community was \$385,000.

Figure 9.7. DISTRIBUTION NETWORK FOR BASE-CASE COMMUNITY

Table 9.49. DISTRIBUTION SYSTEM DATA

Pipe Segment	Length Ft	Peak Flow GPM	Nominal Size In	Pressure Drop ² PSI	Cost ³ \$/FT	Segment Cost ³ \$
A	400	230	4	9.54	17.56	7026
B	150	46	2	4.68	11.42	1713
C	150	92	3	2.47	13.70	2055
D	150	92	3	2.47	13.70	2055
E	150	46	2	4.60	11.42	1713
F	15	46	2	0.46	11.42	171
G	15	46	2	0.46	11.42	171
H	15	46	2	0.46	11.42	171
I	170	46	2	5.30	11.42	1941
J	170	46	2	5.30	11.42	1941
Total Pipe Cost					\$ 18957	
Fittings ⁴					<u>7383</u>	
Total Material					26540	
Installation Cost ⁵					13270	
Valving Costs (Installed)					<u>5000</u>	
TOTAL SYSTEM COST ⁶					\$ 44810	

1. See Figure 4.1

2. At peak flow rate, one direction. System analysis assumed distribution pressure drop of 25 psi. in each direction (supply and return). Maximum drop from piping is 17.31 psi. This allows 7.68 psi for valve and fitting pressure losses (30% of total).

3. Combined cost of supply and return.

4. 40% of pipe cost

5. 50% of material cost, assume open country

6. Pipe, fittings and installation cost data supplied by Klink, R., Perma-Pipe Division of Midwesco, Inc., Niles, Ill., July 1977. Pipe is schedule 40 steel with 1 inch of polyurethane foam in a fiberglass-reinforced plastic casing. Costs were updated to 1979 dollars via M&S equipment index.

Figure 9.8. DISTRIBUTION NETWORK FOR SITE-SPECIFIC COMMUNITY

Table 9.50. DISTRIBUTION SYSTEM DATA -- SITE-SPECIFIC CASE

Thermal Service Provided	Pipe Segment	Length, ft	Peak Flow, (GPM)	Pressure Drop ² (psi)	Nominal Pipe Size, in.	Cost, ³ \$/ft	Segment Cost, ⁴ \$
Heating	A	762	830	6.89	8	40.40	30,784
	B	225	269	7.40	4	17.56	3,951
	C	450	810	3.89	8	40.40	18,180
	D	138	162	6.47	3	13.70	1,890
	E	88	648	4.96	5	21.56	1,897
	F	163	486	5.40	5	21.56	3,514
	G	387	324	6.06	5	21.56	8,344
	H	212	162	9.94	3	13.70	2,904
	I	175	309	7.44	4	17.56	3,073
	J	125	137	4.30	3	13.70	1,713
	K	100	80	8.69	2	11.42	1,142
	L	175	40	4.22	2	11.42	1,998
	M	250	132	8.03	3	13.70	3,425
	N	150	92	2.47	3	13.70	2,055
	O	188	52	7.36	2	11.42	2,147
	P	100	41.6	2.59	2	11.42	1,142
	Q	162	31.2	2.45	2	11.42	1,850
	R	162	15.6	0.68	2	11.42	1,850
	S	300	57.2	14.01	2	11.42	3,426
	T	75	15.6	0.38	2	11.42	857
	U	125	41.6	3.74	3	13.70	1,713
	V	125	26.0	1.36	2	11.42	1,427
	W	163	15.6	0.69	2	11.42	1,862
	Service Piping:						
	High Rise (Five Buildings)	15	162	0.70	3	13.70	1,028
	Low Rise (Five Buildings)	15	40	0.36	2	11.42	857
	Townhouse (42 Units)	30	2.6	0.01	2	11.42	14,389
Cooling	B	225	1,485	24.23	6	25.10	5,648
	C	450	1,655	14.58	8	40.40	18,180
	D	138	331	6.66	4	17.56	2,423
	E	88	1,324	1.89	8	40.40	3,555
	F	163	993	2.05	8	40.40	6,585
	G	387	662	2.30	8	40.40	15,635
	H	212	331	3.45	5	21.56	4,571
	Service Piping:						
	High Rise (Five Buildings)	15	331	0.67	4	17.56	1,317
	DHW	B	223	13.6	2	11.42	2,569

Total Pipe Cost:	\$177,615
Fittings ⁴	71,046
Installation ⁵	107,400
Meters and Valves (Installed)	28,500
Total	\$384,561

1. See Figure 9.8.
2. At peak flow rate, one direction. Thermal distribution system analysis assumed distribution pressure drop of 25 psi in each direction (supply and return) under peak load conditions for each major system segment, except the hot water system serving the residential sector, which was designed with an allowed pressure drop of 100 psi, round trip.
3. Combined cost of supply and return.
4. 40% of pipe cost.
5. 50% of total materials cost, assuming open country. For a second system in the same trench (i.e., a 4-pipe system), 30% of the total material cost was used as the installation factor for the second system.
6. Pipe is Schedule 40 steel with 1-inch polyurethane foam insulation in a fiberglass-reinforced plastic casing. Pipe, fittings, and installation cost data supplied by Klink, R., Perma-Pipe Division of Midwesco, Inc., Niles, Ill., July 1977. Costs were updated to 1979 dollars via M&S equipment index.

9.6.5.3 Distribution System Thermal Losses

Thermal losses through the insulation of the buried piping of the thermal distribution system have a negative impact on system performance because additional primary energy must be consumed to make up these losses. Losses of from 10% to 20% of the thermal distribution system energy throughput are typical of European district heating experience. In this section, the methodology used in the evaluation of HAHP-ICES distribution system thermal losses is presented. The impact of thermal losses on base-case energy use is discussed in Section 3.4.2. The impact of thermal losses on site-specific case energy use is discussed in Section 3.5.2. A loss of 15% of distributed thermal energy was used to explore the impact on HAHP-ICES thermodynamic performance (see Section 3.6). Thermal losses ranging from 0% to 20% of distributed thermal energy were used to explore the impact on base-case HAHP-ICES economics (see Section 4.3.4). The impact of thermal losses calculated by the methodology presented in this section on base and site-specific case economics are discussed in Sections 4.3.4 and 4.5.1, respectively.

Thermal losses arising from the distribution of hot and chilled water for space heating, domestic hot water, and space cooling were estimated based on the procedure in Technical Guidelines for Energy Conservation.^{*} Note that thermal losses were not calculated in the hour by hour simulations of system performance, but were estimated on an annual basis. Because parameters important in the determination of thermal losses from buried pipes (i.e., soil conductivity, soil temperature, depth of pipe, etc.) are quite variable from site to site, the results of an annual estimate are accurate enough to understand the impact of distribution system thermal losses on HAHP-ICES performance and economics.

The heat loss per foot length of buried pipe can be expressed as:

$$Q = K_p (T_p - T_g), \text{ Btu/hr-ft}$$

where —

Q = heat loss per foot length of buried pipe

K_p = heat transfer factor, Btu/hr-ft-°F

T_p = temperature of fluid in pipe, °F

T_g = undisturbed earth temperature.

K_p is given by:

$$\frac{1}{K_p} = \frac{1}{C} + \frac{6}{\pi k_s} \ln \frac{d}{r} + [(d/r)^2 - 1]^{1/2}$$

* Technical Guidelines for Energy Conservation, National Bureau of Standards, AD/A-041 668, U.S. Department of Commerce, National Technical Information Service, June 1977.

where -

C = thermal conductance of pipe and insulation, Btu/hr-ft²-°F

d = distance of ground surface to center of pipe, inches

k_s = thermal conductivity of undisturbed earth, $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$

$$1/C = \frac{1}{h_i 2\pi r_i} + \frac{6}{\pi} \frac{1}{k_w} \ln \left(\frac{D}{D-2 t_w} \right) + \frac{1}{k_I} \ln \left(\frac{D+2 t_I}{D} \right)$$

where -

h_i = surface conductance at the inside surface of pipe, water side, Btu/hr-ft²-°F

r_i = inside radius of pipe, inches

k_w = pipe thermal conductivity, $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$

D = pipe outside diameter, inches

t_w = pipe wall thickness, inches

k_I = thermal conductivity of insulation, $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$

t_I = insulation thickness, inches.

Values for K_p, the heat loss factor, were calculated using the following assumed values:

d = 72 inches

k_s = 10.8 $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$

k_w = 360 $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$

h_i = 2000 $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$

Insulation thickness and material = 1 inch polyurethane.*

k_I = 0.12 $\frac{\text{Btu-in.}}{\text{hr-ft}^2\text{-°F}}$

T_g = 50°F (heating season)

T_g = 55°F (cooling season)

T_p = 190°F (sendout - heating and domestic hot water)

T_p = 170°F (return - heating and domestic hot water)

T_p = 44°F (sendout - chilled water for cooling)

T_p = 55°F (return - chilled water for cooling).

Values for K_p are summarized in Table 9.51.

* For 8-inch diameter pipe, this is a conservative value. The 8-inch pipe had 1.5 inches of polyurethane insulation.

Table 9.51. VALUES FOR K_p : PIPE HEAT LOSS FACTOR FOR VARIOUS PIPE SIZES

Nominal Pipe Size, in.	K_p , $\frac{\text{Btu}}{\text{hr-ft}^2-\text{°F}}$
2	0.096
3	0.127
4	0.153
5	0.181
6	0.207
8	0.256

The net gains or losses from the hot and chilled water pipes are summarized in Table 9.52. For a 190°F sendout temperature, losses range from 13.4 Btu/hr-ft for 2-inch pipe to 35.8 Btu/hr-ft for 8-inch pipe. For a 170°F return temperature, losses range from 11.5 Btu/hr-ft for 2-inch pipe to 30.7 Btu/hr-ft for 8-inch pipe. The chilled water sendout pipe, at 44°F, gains heat from the earth. Heat gains range from 1.06 Btu/hr-ft for a 2-inch pipe to 2.82 Btu/hr-ft for an 8-inch pipe. Note that the return chilled water piping has no gains or losses since the return temperature of 55°F is the same as the ground temperature.

Table 9.52. THERMAL LOSS RATES FROM HAHP-ICES DISTRIBUTION SYSTEM

Nominal Pipe Size, in.	Thermal Loss Rate, 190°F, Btu/hr-ft	Thermal Loss Rate, 170°F, Btu/hr-ft	Thermal Loss Rate, 44°F, Btu/hr-ft, Heat Gain
2	13.44	11.52	1.06
3	17.78	15.24	1.40
4	21.42	18.36	1.68
5	25.34	21.72	1.99
6	28.98	24.84	2.28
8	35.84	30.72	2.82

Annual heat loss values for the base and site-specific case thermal distribution systems were calculated for 8760 hours of hot water distribution because distribution piping carried domestic hot water to loads in the community at all times. There were no chilled water distribution system heat gains associated with the base case community because only the office building was provided with chilled water and because the central plant was housed in the office building, all heat gains to the chilled water piping served the office building cooling load. Site-specific community chilled water distribution system heat gains were calculated for 1480, 3576, and 1135 hours of chilled water distribution to the retail space, the office building, and the high-rise residences, respectively.

9.6.5.4 Distribution System Energy Burdens

Pump work for the distribution of hot and chilled water for domestic hot water (DHW), and for the cooling tower was calculated under the following assumptions:

- Pump work in KW = $\frac{\dot{m} \Delta H}{2310}$

where —

$\dot{m}$ = flow rate in gallons per minute (GPM)

ΔH = system pressure drop in feet of head.

- Flow rate, $\dot{m} = \frac{Q}{480 \Delta T}$

where —

Q = thermal load in Btu/hr

ΔT = temperature difference between sendout and return temperatures to the load, °F.

- For DHW, $\dot{m}$ = demand for hot water in GPM.

- Pressure drops in the cooling tower piping, hot and chilled water piping, and DHW water piping were held constant at their values for peak flow rates. Pressure drops are summarized in Table 9.53.

Table 9.53 . COOLING TOWER AND DISTRIBUTION SYSTEM PRESSURE DROPS
IN BASE AND SITE-SPECIFIC CASES

<u>Load</u>	<u>Round Trip Pressure Drop (Feet of Head)</u>	
	<u>Base Case</u>	<u>Site-Specific Case</u>
Cooling Tower	32	32
Office Heating & Cooling	N.A. ^a	34
Office (DHW)	N.A. ^a	20
High-rise (Heating, Cooling and DHW)	N.A. ^b	120
Low-rise & Townhouse (Heating and DHW)	120 ^c	120 ^d
Retail (Heating & Cooling)	N.A. ^b	120

^a Not applicable. In base case, loads are served by pumps that are part of the office building's physical plant, not part of the HAHP-ICES central plant.

^b Not applicable. No high-rise dwellings or retail space in base case.

^c Low-rise only, no townhouse in base case.

^d Because of the layout of the site-specific distribution system (see Figure 9.8), pump work associated with the high-rise, low-rise, and townhouse loads (during the heating season and for DHW during the cooling season) is:

$$\text{Pump Work (HP)} = [(\text{Total flow (GPM) to high-rise, townhouse, and low-rise for heating and DHW (heating season) or DHW only (cooling season)} \times (\Delta H = 120 \text{ ft}) + \text{flow (GPM) to townhouse and low-rise for heating and DHW (heating season) or DHW only (cooling season)} \times (\Delta H = 120 \text{ ft}))] / 2310.$$

9.6.6 Steam Turbine Efficiency Curve

The prime mover for the heat-pump in the HAHP-ICES is a 90-hp steam turbine. The efficiency curve of the turbine at full load has been developed as a function of condenser temperature and is shown in Figure 9.9.

9.6.7 HAHP-ICES Cooling Performance Evaluation (Central Plant)

Full and part load HAHP-ICES cooling performance was evaluated using the following approach:

- Full load mechanical cooling output = (Cooling COP at full load)(78.76 hp)
- Compressor horsepower for all other loads =
$$(\text{Cooling load})/[(\text{Cooling COP at full load})(\text{CF})] \quad (9-1)$$

where -

CF = part load cooling COP correction factor

$$\text{CF} = A + BX + CX^2 + DX^3 \quad (9-2)$$

where -

X = (cooling load/full load cooling capacity) X 100

$$A = -2.817 \times 10^{-1}$$

$$B = 4.258 \times 10^{-2}$$

$$C = -5.600 \times 10^{-4}$$

$$D = 2.626 \times 10^{-6}$$

- Full load mechanical performance

Ambient Temperature, °F

Cooling COP at Full Load*

+60	5.8
+70	4.9
+80	4.5
+90	4.1
+100	3.8

Full load cooling performance of HAHP-ICES is reported in Section 3.1.2. Part load compressor horsepower requirements as a function of cooling output is shown in Figure 9.10.

* COP's do not include cooling tower fan loads.

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* MECHANICAL CONVERSION EFFICIENCY.

Figure 9.9. HEAT ENGINE EFFICIENCY AT FULL LOAD VERSUS CONDENSER TEMPERATURE

Figure 9.10. PERFORMANCE OF HEAT PUMP IN COOLING MODE — COMPRESSOR HORSEPOWER VERSUS COOLING OUTPUT
 $60 \leq T_{amb} \leq 100^{\circ}\text{F}$

9.6.8 HAHP-ICES Heating Performance Evaluation With Internal Heat Recovery (Central Plant)

Full and part load HAHP-ICES heating performance with internal heat recovery was evaluated using the following approach:

- Calculate full load cooling output = [(Cooling COP at full load)(78.76 hp)]
- Calculate required horsepower (hp) for all other loads:

$$hp = (\text{Cooling load}) / [(\text{Cooling COP at full load})(CF)] \quad (9.3)$$

- Refrigerant condenser heat at any load = load + hp (2545.1)
- Full load mechanical performance

<u>Ambient Temperature, °F</u>	<u>Heating COP at Full Load</u>
-10	4.00
0	4.00
+10	4.00
+20	4.00
+30	3.30
+40	3.65
+50	4.00
+60	4.00

Full load heating performance of HAHP-ICES with internal heat recovery is reported in Section 3.1.3. Part load heating performance with internal heat recovery is shown in Figures 9.11, 9.12, 9.13, and 9.14.

9.6.9 HAHP-ICES Performance With Outside Heat Recovery (Central Plant) (Two-Stage Heat Pump Performance)

Full and part load HAHP-ICES performance using ambient air as a heat source was developed using the following approach:

- In outside heat recovery operation, the condenser of the outside compressor is the heat source to the evaporator of the inside compressor.
- The performance of the two-stage heat pump is based on the fact that the condenser heat from the outside compressor (C_1) is equal to the input to the evaporator of the inside compressor (C_2).
- The maximum horsepower draw from the outside compressor is 16. Resulting from limiting the outside compressor horsepower to 16 hp, at ambient temperatures below 30°F, the combined compressors cannot utilize the maximum available horsepower from the turbine, i.e., 78.76 hp.

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Figure 9.11. PERFORMANCE OF HEAT PUMP WITH INTERNAL HEAT RECOVERY
AT AMBIENT TEMPERATURE BELOW 30°F AND 50°F AND ABOVE

Figure 9.12. PERFORMANCE OF HEAT PUMP WITH INTERNAL HEAT RECOVERY AT AMBIENT TEMPERATURE OF 45°F

Figure 9.13. PERFORMANCE OF HEAT PUMP WITH INTERNAL HEAT RECOVERY AT AMBIENT TEMPERATURE OF 35°F

Figure 9.14. PERFORMANCE OF HEAT PUMP WITH INTERNAL HEAT RECOVERY AT AMBIENT TEMPERATURE OF 30°F

For example, at an ambient temperature of 0°F, total horsepower input to both compressors is 58.17 hp.

- Full load mechanical performance

<u>Ambient Temperature, °F</u>	<u>Cooling COP at Full Load For Outside Compressor</u>
-10	3.05
0	3.60
+10	4.25
+20	5.15
+30	6.45
+40	8.45
+50	12.50
+60	12.50

- The heating COP of the inside compressor in two-stage operation corresponds exactly to the heating COP of the compressor (as a function of ambient temperature) used alone for internal heat recovery because its evaporator temperature is the same in either configuration.

- The calculation procedure is, in brief (for each ambient temperature):

1. Calculate full load cooling of C_2 :

$$\text{Full Load Cooling 2} = (\text{COP}_2^{\text{cool}} \text{ at full load})(78.76)$$

2. Calculate hp 2 versus cooling load (CL_2):

$$\text{hp 2} = (CL_2) / [(\text{COP}_2^{\text{cool}} \text{ at full load})(CF)]$$

3. Heat out 2 = hp 2 + CL_2

4. Calculate full load of C_1 . This occurs when:

$$- CF_1 = 1.0$$

$$- \text{COP}_1^{\text{cool}} = \text{full load value}$$

$$- \text{Heat out 1} = CL_2$$

$$- \text{hp 1} + \text{hp 2} = 78.76 \text{ hp; or hp 1 (maximum)} = 16 \text{ hp}$$

5. Calculate hp 1 versus cooling load (CL_1):

$$\text{hp 1} = (CL_1) / [(\text{COP}_1^{\text{cool}} \text{ at full load})(CF_1)]$$

6. Heat out 1 = hp 1 + CL_1

7. To calculate overall performance:

$$- \text{Find hp 1 and hp 2 at each point where heat out 1} = CL_2$$

$$- \text{Total horsepower input to compressors} = \text{hp 1} + \text{hp 2}$$

$$- \text{Total heat out} = \text{hp 2} + CL_2$$

Full load heating performance of HAHP-ICES using outside air as a heat source is reported in Section 3.1.4. Part load performance with heat recovery from outside air is shown in Figure 9.15.

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Figure 9.15. HEATING PERFORMANCE OF THE HAHP-ICES CENTRAL PLANT IN EXTERNAL HEAT PUMP MODE FOR DIFFERENT OUTSIDE TEMPERATURES

9.6.10 Supplemental Cooling System Capacity and Performance — Base Case

In the base case, supplemental cooling to meet peak cooling loads is provided by an electric motor-driven compressor rated at 126 hp. With a 91% efficient drive motor, full-load input to the supplemental compressor is 103.3 kW. Performance of the supplemental electric chiller used in the base case is summarized in Table 9.54. Cooling output of the supplemental, 126 hp mechanical chiller is from 1.86×10^6 Btu/hr at an ambient temperature of 60°F to 1.22×10^6 Btu/hr at 100°F. Total cooling output (turbine-driven mechanical chiller plus electrically-driven chiller) ranges from 3.02×10^6 Btu/hr at 60°F to 1.98×10^6 Btu/hr at 100°F. Part-load characteristics of the supplemental electric chiller are comparable to those of the steam turbine-driven compressor.

Table 9.54. FULL-LOAD COOLING PERFORMANCE OF SUPPLEMENTAL ELECTRIC CHILLER AND TOTAL SYSTEM COOLING CAPACITY — BASE CASE

Ambient Temperature, °F	Full-Load 126-hp Electric Chiller Cooling Output, X 10^6 Btu/hr	Total Peak-Load Cooling Output, X 10^6 Btu/hr*
60	1.860	3.023
70	1.564	2.541
80	1.428	2.321
90	1.309	2.128
100	1.216	1.976

* Turbine-driven chiller + supplemental electric chiller.

9.6.11 Supplemental Cooling System Capacity and Performance — Site-Specific Case

In the site-specific case, supplemental cooling is provided by two electric driven chillers. Two chillers are used to achieve a minimization of part-load inefficiencies. Backup chiller capacities, as a function of the number of turbines used to serve the site-specific community, are summarized in Table 9.55. Backup chiller capacities are sized so that the smaller chiller is about 30% of the capacity of the larger chiller; total turbine-driven chiller and supplemental chiller capacity is 10.3×10^6 Btu/hr (860 tons) at 90°F ambient. The efficiency of the electric motor driving the compressor is assumed to be 91%. Supplemental electric chillers have part-load characteristics comparable to those of the turbine-driven compressor. Each backup chiller is equipped with a cooling tower sized to handle the refrigerant condenser load.

Table 9.55. COMPONENT SIZES USED IN PERFORMANCE EVALUATION
OF HAHP-ICES; SITE-SPECIFIC CASE

<u>Number of Turbines</u>	<u>Capacity (Output) of Peak Electric Chiller #1 (Btu/hr) at 90°F Ambient</u>	<u>Capacity (Output) of Peak Electric Chiller #2 (Btu/hr) at 90°F Ambient</u>
0	8.04×10^6	2.26×10^6
1	7.42×10^6	2.06×10^6
2	6.81×10^6	1.85×10^6
3	6.2×10^6	1.65×10^6
4	5.6×10^6	1.44×10^6

9.6.12 Supplemental Heating Capacity — Base Case

Peak heating requirements in the base case are met by low-pressure boilers with full load efficiencies of 83%. Part load performance of the backup boiler was discussed in Section 9.6.3.

Base-case peak heating needs are met by an auxiliary boiler with a full load input of 2.5×10^6 Btu/hr, and, at 83% efficiency, an output of 2.07×10^6 Btu/hr. Corresponding peak load total heating capacity is 3.31×10^6 Btu/hr at 30°F in internal heat recovery operation; 3.12×10^6 Btu/hr in external air source operation. Overall peak load heating COP, based on total boiler input, is 0.94 at 30°F in internal heat recovery operation, and 0.88 in external air source operation. Peak load COP's do not include distribution pumping or cooling tower fan loads.

9.6.13 Supplemental Heating Capacity — Site-Specific Case

Peak heating requirements in the site-specific case are met by low-pressure boilers with full load efficiencies of 83%. Part load performance of the backup boiler was discussed in Section 9.6.3.

In the site-specific case, total backup boiler capacity is a function of the number of turbines used. Two boilers are used, the smaller sized at about one-third the capacity of the larger unit in order to minimize part load efficiency penalties. Backup capacity, as a function of the number of turbines serving the load, is given in Table 9.56. Total output of turbines plus total backup boiler capacity is about 18×10^6 Btu/hr.

Table 9.56. SUPPLEMENTAL BOILER COMPONENT SIZES
USED IN PERFORMANCE EVALUATION OF HAHP-ICES; SITE-SPECIFIC CASE

<u>Number of Turbines</u>	<u>Capacity (Input) of Auxiliary Boiler #1 (10⁶ Btu/hr)</u>	<u>Capacity (Input) of Auxiliary Boiler #2 (10⁶ Btu/hr)</u>
0	13.37	4.62
1	13.50	4.25
2	12.37	3.87
3	11.0	3.5
4	9.88	3.13

9.6.14 Absorption Chiller Performance Site Specific Case

An absorption chiller operated off turbine condenser heat may be used to improve the thermodynamic efficiency of the central plant by utilizing turbine condenser heat that would ordinarily be rejected at the cooling tower during the cooling season. In doing so, the turbine efficiency would be reduced from 0.296 to 0.22 because turbine condenser temperature must be raised to 200°F from 150°F in order to actuate the absorption chiller. Nominal full-load absorption chiller COP is 0.7. Absorption chiller performance is summarized in Table 9.57. The absorption chiller may also be fired directly by the boiler if insufficient turbine condenser heat is available. In the site-specific case, overall system performance was examined with and without an absorption chiller to explore the potential energy and economic benefits of using an absorption chiller in the central plant.

Table 9.57. ABSORPTION CHILLER PERFORMANCE — SITE-SPECIFIC CASE

<u>Ambient Temperature, °F</u>	<u>COP_{cool}</u>
60	0.6
70	0.65
80	0.7
90	0.7
100	0.7

Part load correction factor = 1.0 for 40% ≤ loads ≤ 100%.

Below 40% load, absorption chiller is shut off.

Cooling COP does not include absorption chiller parasitic loads.

9.6.15 Modes of Operation — Office Building Conventional HVAC System — Base and Site-Specific Cases

The description of the operation of the office building conventional HVAC system operation, discussed in this section, and the discussion of system operating sequence in Section 9.6.16 is applicable to both the base and site-specific office buildings.

9.6.15.1 Cooling Only

The supply air is cooled and dehumidified at the air-handling units and ducted through the building to the variable volume units, where it is metered to match or balance the cooling loads of the spaces. The heat removed by the chiller is rejected from the building through the cooling tower.

9.6.15.2 Cooling During Operating Hours With Heating at Night

The cooling system operates as above, but the heat removed by the chiller is used to heat the water in the water storage tank. The water from the tank is then used to heat the building through the perimeter system during the unoccupied hours. Note that there is no economizer cycle used here, i.e., the refrigeration equipment is used to cool the building even though the outside air temperature might be able to provide "free" cooling. Instead, the heat of the day is used during the cool of the night with a resulting increase in coefficient of performance.

9.6.15.3 Cooling and Heating Above the System Balance Point

The system balance point is the ambient temperature where heat recovered from internal cooling loads is just equal to building heat loads. Operation of the system in this mode is similar to that described in Section 9.6.15.2, except that now some of the rejected heat is used in the perimeter heating system, with the remainder used to heat the storage water. It is obvious that as the balance point is approached, less heat will be stored for unoccupied hours use and consequently, this deficiency will have to be made up by the boiler. Here again, the use of an "economizer" would be counter-productive.

9.6.15.4 Cooling and Heating Below the System Balance Point

Below the system balance point, the heat recovered from internal cooling loads is not sufficient to meet the heating requirements of the building. In this mode, the operation of the system is similar to that discussed in Section 9.6.15.3, except that all the heat removed by the chiller is used in the perimeter heating system with the additional heat required supplied by the boiler.

9.6.16 System Operation Sequence — Office Building Conventional HVAC System

The day-by-day sequence is operated by a 7-day timer with an override timer switch. The system would generally be set to operate on a 12-hour interval with the cooling shut down at night. Typically, during the heating months, the air-handling units start about one hour before the start of the business day. This serves to circulate the building air, especially the air trapped between the top floor ceiling and the roof. The building interior lighting would next be

energized and the interior cooling load will increase. About one-half hour before occupancy, the chiller is turned on and the VAV terminals respond to the now present cooling load. As the building's population increases and the solar loads commence, the VAV terminals increase the air supply to match the cooling requirements.

During the cooling season, the sequence is similar except that it is not mandatory that the air-handling units circulate air prior to chiller start-up. What will happen is that the VAV terminals will respond to the hot building interior by going full open until room conditions are met, then throttle back to controlled operation.

9.6.17 Performance of Conventional Components and HAHP-ICES Under Peak Heating and Cooling Load Conditions; Base and Site-Specific Cases

Tables 9.58 to 9.67 summarize input/output performance of conventional components and HAHP-ICES under peak heating and cooling load conditions for both base and site-specific cases. Overall community COP's based on total primary input are reported in Section 3.2.6.

Table 9.58. PEAK LOAD PERFORMANCE OF BASE CASE SYSTEM - CONVENTIONAL COMPONENTS; HEATING MODE AT AMBIENT TEMPERATURE OF 30°F

Building Type	Number of Dwelling Units	Heating System Type	Heating System Input, Btu/hr	Heating System Primary Input, ^a Btu/hr	Heating System Output, Btu/hr	Total Heating System Primary Input, Btu/hr	Total Heating System Output, Btu/hr
Low-Rise	120 Units in 5 Buildings	Gas Furnace,	30,000	31,579	22,500	3.79×10^6	2.70×10^6
		Gas Water Heater	40,000	42,105	28,000	5.05×10^6	3.36×10^6
Office Case I ^b	1 Building of 59,000 ft ² floor space	Electric Boiler	(330 Kw _e) 1.13×10^6	3.79×10^6	1.13×10^6	3.79×10^6	1.13×10^6
Office Case II ^c	1 Building of 59,000 ft ² floor space	Electric Heat Reclaim Chiller	(79.5 Kw _e) 0.27×10^6	9.14×10^5	1.09×10^6	9.14×10^5	1.09×10^6

^a Conversion factor for primary input for gas was 0.95; conversion factor for primary input for resources to generate electricity was 0.2968.

^b Assumes 100% of office heating load from electric boiler; assumes no internal cooling load available to heat reclaim chiller. A worst case configuration.

^c Assumes an internal cooling load of sufficient size to drive heat reclaim chiller to full load output. A best case configuration.

Table 9.59. PEAK LOAD PERFORMANCE OF BASE CASE SYSTEM — CONVENTIONAL COMPONENTS; COOLING MODE AT AMBIENT TEMPERATURE OF 90°F

<u>Building Type</u>	<u>Number of Dwelling Units</u>	<u>Cooling System Type</u>	<u>Cooling System Input, E_u/hr</u>	<u>Cooling System Primary Input, Btu/hr</u>	<u>Cooling System Output, Btu/hr</u>	<u>Total Cooling System Primary Input, Btu/hr</u>	<u>Total Cooling System Output, Btu/hr</u>
Office ^b	1 Office 59,000 ft ²	Electric Chiller	(150.8 Kw _e) 5.15 X 10 ⁵	1.73 X 10 ⁶	1.76 X 10 ⁶	1.73 X 10 ⁶	1.76 X 10 ⁶

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

^b No cooling supplied to low-rise building.

Table 9.60. PEAK LOAD PERFORMANCE OF BASE CASE SYSTEM — HAHP-ICES;
HEATING MODE AT AMBIENT TEMPERATURE OF 30°F*

Heating System Type	Number of Dwelling Units	Heating System Input, Btu/hr	Heating System Primary Input ^a Btu/hr	Heating System Output, Btu/hr	Total Heating System Primary Input, Btu/hr	Total Heating System Output Btu/hr
HAHP-ICES ^b Case I	120 low-rise; One 59,000 ft ² office	Heat Pump: 1.02 X 10 ⁶ Supplemental Boilers: 2.5 X 10 ⁶	Heat Pump: 1.07 X 10 ⁶ Supplemental Boilers: 2.63 X 10 ⁶	Heat Pump: 1.24 X 10 ⁶ Supplemental Boilers: 2.07 X 10 ⁶	3.70 X 10 ⁶	3.31 X 10 ⁶
HAHP-ICES ^c Case II	120 low-rise; One 59,000 ft ² office	Heat Pump: 1.02 X 10 ⁶ Supplemental Boilers: 2.5 X 10 ⁶	Heat Pump: 1.07 X 10 ⁶ Supplemental Boilers: 2.63 X 10 ⁶	Heat Pump: 1.05 X 10 ⁶ Supplemental Boilers: 2.07 X 10 ⁶	3.70 X 10 ⁶	3.12 X 10 ⁶

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

^b Assumes an internal cooling load available in office building to drive heat pump to full load output. A best case configuration.

^c Assumes an external (ambient air) source for the heat pump. A worst case configuration.

* Values do not reflect distribution thermal losses, distribution pumping loads, and cooling tower fan and pumping loads.

Table 9.61. PEAK LOAD PERFORMANCE OF BASE CASE SYSTEM - HAHP-ICES;
COOLING MODE AT AMBIENT TEMPERATURE OF 90°F*

Cooling System Type	Number of Dwelling Units	Cooling System Input, Btu/hr	Cooling System Primary Input ^a Btu/hr	Cooling System Output, Btu/hr	Total Cooling System Primary Input, Btu/hr	Total Cooling System Output Btu/hr
HAHP-ICES	One 59,000 ft ² office ^b	Heat Pump: 0.93 X 10 ⁶	Heat Pump: 9.8 X 10 ⁵	Heat Pump: 0.82 X 10 ⁶	2.17 X 10 ⁶	2.13 X 10 ⁶
		Supplemental Electric Chiller: 3.53 X 10 ⁵	Supplemental Electric Chiller: 1.19 X 10 ⁶	Supplemental Electric Chiller: 1.309 X 10 ⁶		

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

^b No cooling supplied to low-rise building.

* Values do not reflect distribution thermal losses, distribution pumping loads, and cooling tower fan and pumping loads.

Table 9.62. PEAK LOAD PERFORMANCE OF SITE-SPECIFIC SYSTEM — CONVENTIONAL COMPONENTS; HEATING AT AMBIENT TEMPERATURE OF 30°F

Building Type	Number of Dwelling Units	Heating System Type	Heating System Input, Btu/hr	Heating System Primary Input, Btu/hr	Heating System Output, Btu/hr	Total Heating System Primary Input, Btu/hr	Total Heating System Output, Btu/hr
Office ^b Case I	1 Building ² of 124,000 ft ² floor space	2-Electric Boilers	(2 X 330 Kw _e) 2.25 X 10 ⁶	7.59 X 10 ⁶	2.25 X 10 ⁶	7.59 X 10 ⁶	2.25 X 10 ⁶
Office ^c Case II	1 Building ² of 124,000 ft ² floor space	Electric Heat Reclaim Chiller	(167 Kw _e) 0.57 X 10 ⁶	1.92 X 10 ⁶	2.29 X 10 ⁶	1.92 X 10 ⁶	2.29 X 10 ⁶
High-Rise	520 Units in 5 Buildings	Gas Boiler, 2-35 hp Boilers per Building, Total Capacity 350 hp	1.17 X 10 ⁷	1.23 X 10 ⁷	9.72 X 10 ⁶	1.23 X 10 ⁷	9.72 X 10 ⁶
Retail Store	1 Building, 135,000 ft ² floor space	Gas Boiler, 115 hp	3.85 X 10 ⁶	4.05 X 10 ⁶	3.19 X 10 ⁶	4.05 X 10 ⁶	3.19 X 10 ⁶
Low-Rise	120 Units in 5 Buildings	Gas Furnace Gas Water Heater	30,000 40,000	31,579 42,105	22,500 28,000	3.79 X 10 ⁶ 5.05 X 10 ⁶	2.70 X 10 ⁶ 3.36 X 10 ⁶
Town-house	42	Gas Furnace Gas Water Heater	50,000 40,000	52,632 42,105	37,500 28,000	2.21 X 10 ⁶ 1.77 X 10 ⁶	1.58 X 10 ⁶ 1.18 X 10 ⁶

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

^b Assumes 100% of office heating load from electric boiler; assumes no internal cooling load in office building available to heat reclaim chiller. A worst case configuration.

^c Assumes an internal cooling load of sufficient size to drive heat reclaim chiller to full load output. A best case configuration.

Table 9.63. PEAK LOAD PERFORMANCE OF SITE-SPECIFIC SYSTEM --
CONVENTIONAL COMPONENTS; COOLING MODE AT AMBIENT TEMPERATURE OF 90°F

Building Type ^a	Number of Dwelling Units	Cooling System Type	Cooling System Input, Btu/hr	Cooling System Primary Input, ^b Btu/hr	Cooling System Output, Btu/hr	Total Cooling System Primary Input, Btu/hr	Total Cooling System Output, Btu/hr
Office	1 Building 124,000 ft ² floor space	Electric Chiller	(319.3 Kw _e) 1.09 X 10 ⁶	3.67 X 10 ⁶	3.72 X 10 ⁶	3.67 X 10 ⁶	3.72 X 10 ⁶
High-Rise	520 Units in 5 Buildings	Electric Chiller	5 Chillers, 128.8 Kw _e / Chiller Total: 2.20 X 10 ⁶	7.41 X 10 ⁶	7.50 X 10 ⁶	7.41 X 10 ⁶	7.50 X 10 ⁶
Retail	1 Building 135,000 ft ² floor space	Electric Chiller	(319.3 Kw _e) 1.09 X 10 ⁶	3.67 X 10 ⁶	3.72 X 10 ⁶	3.67 X 10 ⁶	3.72 X 10 ⁶

^a No cooling supplied to low-rise buildings or townhouse dwellings.

^b Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

Table 9.64. PEAK LOAD PERFORMANCE OF SITE-SPECIFIC SYSTEM — HAHP-ICES;
HEATING MODE AT AMBIENT TEMPERATURE OF 30°F; ONE STEAM TURBINE/HEAT PUMP CASE*

Heating System Type	Heating System Input, Btu/hr	Heating System Primary Input ^a Btu/hr	Heating System Output, Btu/hr	Total Heating System Primary Input, Btu/hr	Total Heating System Output Btu/hr
HAHP-ICES ^b Case I	Heat Pump: 1.02 X 10 ⁶ Supplemental Boilers: 1.78 X 10 ⁷	1.98 X 10 ⁷	Heat Pump: 1.24 X 10 ⁶ Supplemental Boilers: 1.47 X 10 ⁷	1.98 X 10 ⁷	1.60 X 10 ⁷
HAHP-ICES ^c Case II	Heat Pump: 1.02 X 10 ⁶ Supplemental Boilers: 1.78 X 10 ⁷	1.98 X 10 ⁷	Heat Pump: 1.05 X 10 ⁶ Supplemental Boilers: 1.47 X 10 ⁷	1.98 X 10 ⁷	1.58 X 10 ⁷

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

^b Assumes an internal cooling load from office building available to drive heat pump to full load output. A best case configuration.

^c Assumes an external (ambient air) source for the heat pump. A worst case configuration.

* Values do not reflect distribution thermal losses, distribution pumping loads, and cooling tower fan and pumping loads.

Table 9.65. PEAK LOAD PERFORMANCE OF SITE-SPECIFIC SYSTEM — HAHP-ICES;
HEATING MODE AT AMBIENT TEMPERATURE OF 30°F; FOUR STEAM TURBINE/HEAT PUMP CASE*

Heating System Type	Heating System Input, Btu/hr	Heating System Primary Input ^a Btu/hr	Heating System Output, Btu/hr	Total Heating System Primary Input, Btu/hr	Total Heating System Output Btu/hr
HAHP-ICES ^b	Heat Pump: 4 turbines at 1.02×10^5 /turbine or 4.08×10^6 Supplemental Boilers: 1.30×10^7	Heat Pump: 4.29×10^6 Supplemental Boilers: 1.37×10^7	Heat Pump: 3.73×10^6 Supplemental Boilers: 1.08×10^7	1.80×10^7	1.45×10^7

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

^b In the four steam turbine/heat pump case, one turbine produces electricity; only turbine waste heat is available. Three turbines operate from external (ambient air) source.

* Values do not reflect distribution thermal losses, distribution pumping loads, and cooling tower fan and pumping loads.

Table 9.66. PEAK LOAD PERFORMANCE OF SITE-SPECIFIC SYSTEM -- HAHP-ICES;
COOLING MODE AT AMBIENT TEMPERATURE OF 90°F; ONE STEAM TURBINE/HEAT PUMP CASE*

Cooling System Type	Cooling System Input, Btu/hr	Cooling System Primary Input ^a Btu/hr	Cooling System Output, Btu/hr	Total Cooling System Primary Input, Btu/hr	Total Cooling System Output Btu/hr
HAHP-ICES	Heat Pump: 0.93×10^6	Heat Pump: 9.81×10^5	Heat Pump: 0.82×10^6	9.57×10^6	1.03×10^7
	Supplemental Chillers: 2.55×10^6	Supplemental Chillers: 8.59×10^6	Supplemental Chillers: 9.48×10^6		

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

* Values do not reflect distribution thermal losses, distribution pumping loads, and cooling tower fan and pumping loads.

Table 9.67. PEAK LOAD PERFORMANCE OF SITE-SPECIFIC SYSTEM - HAHP-ICES;
COOLING MODE AT AMBIENT TEMPERATURE OF 90°F; FOUR STEAM TURBINE/HEAT PUMP CASE*

Cooling System Type	Cooling System Input, Btu/hr	Cooling System Primary Input ^a Btu/hr	Cooling System Output, Btu/hr	Total Cooling System Primary Input, Btu/hr	Total Cooling System Output Btu/hr
HAHP-ICES	Heat Pump: (4 X 0.93 X 10 ⁶) 3.73 X 10 ⁶	Heat Pump: (4 X 9.31 X 10 ⁵) 3.93 X 10 ⁶	Heat Pump: (4 X 0.82 X 10 ⁶) 3.28 X 10 ⁶	1.03 X 10 ⁷	1.03 X 10 ⁷
	Supplemental Chillers: 1.90 X 10 ⁶	Supplemental Chillers: 6.38 X 10 ⁶	Supplemental Chillers: 7.04 X 10 ⁶		

^a Conversion factor for primary input for gas was 0.95. Conversion factor for primary resources to generate electricity was 0.2968.

* Values do not reflect distribution thermal losses, distribution pumping loads, and cooling tower fan and pumping loads.

Distribution

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