MASTER

HEAT PUMP CENTERED INTEGRATED COMMUNITY ENERGY SYSTEMS

System Development

Franklin Research Center Interim Report

ARGONNE NATIONAL LABORATORY

**ENERGY AND ENVIRONMENTAL SYSTEMS
DIVISION**

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HEAT PUMP CENTERED
INTEGRATED COMMUNITY ENERGY SYSTEMS
System Development
Franklin Research Center Interim Report

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PREFACE

As the once popular perception of fuel being cheap and unlimited fades, increased emphasis is being given to more efficient use of energy resources and to the substitution of non-scarce energy forms for depleting and less abundant sources. Recognition of the need to conserve energy resources has been spurred in large part by the oil embargo of 1973 and subsequent escalation in fuel prices, by energy shortages in the harsh winter of 1976/77, by increasing electricity "brown-outs" in urban centers, and by the crippling effects of labor strikes and stoppages in energy supply industries. In recent years, development and acceptance of energy conserving systems which avoid dependence on scarce or interruptible fuels has increased markedly in the United States.

One comprehensive approach to energy conservation is the Integrated Community Energy Systems (ICES) concept, which is intended to increase the efficiency of the varied ways in which energy is provided to and utilized by a community. At the same time, the ICES approach seeks to reduce dependence on scarce fuels and other resources, to preserve environmental quality, to offer energy and energy consuming services in an economically attractive manner, and, perhaps most importantly, to meet the energy needs of communities without adversely affecting social and lifestyle objectives.

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 correctly 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 supply 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 deemed necessary and 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 neither arbitrarily defines the energy services to be provided nor the type, size, or function of the area to be served. As a result, an ICES is tailored for each application and 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.

The communities which ICES are intended to serve consist of multiple facilities in the residential, commercial, industrial, agricultural, recreational, or institutional sectors or in some combination of sectors.

Furthermore, these communities may be in various stages of development, e.g., planned, designed, constructed, or redevelopment.

Heat Pump Centered Integrated Community Energy Systems are energy systems for communities which provide heating, cooling, and/or other 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 are viewed as having significant potential for energy conservation. Furthermore, since conventional building heating and cooling systems would be replaced by this community energy system, nonscarce resources could be used instead of depleting fuels which are in short supply. This is accomplished by powering the heat pumps with nonscarce energy forms not practical for use in the smaller conventional systems. Secondary benefits expected to enhance the value of such systems include reduction of adverse environmental effects over conventional systems, reliable production of services in view of increasingly frequent utility curtailments and interruptions, and provision of services at costs more favorable to consumers than conventional system costs (including acquisition, operation, and maintenance).

The report which follows is 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 1983. 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 Branch, Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Systems, U. S. Department of Energy (DOE). It is a part of the Community Systems Program and is managed by the Energy and Environmental Systems Division of Argonne National Laboratory.

Nine parallel concepts are under development in the initial, System Development, phase. The report which follows presents the interim findings in the development and analysis of a concept being developed by the Franklin Research Center and R. G. Werden and Associates.

1. EXECUTIVE SUMMARY

The concept of a heat pump centered integrated community energy system (HP-ICES) was explored based on a reference community located in the Northeast with a population of 10,000. Engineering and economic analyses were performed for the HP-ICES and for conventional heating/cooling systems. Sensitivity analyses were used to determine variations in results from changes in:

- Community size
- Community energy density
- Waste heat utilization
- Energy cost escalation
- Maintenance and operating personnel
- Central HP-ICES ownership.

Table 1-1 shows how each of the critical parameters affects economic viability of HP-ICES. The results are independent of community size and are only slightly affected by the provision or elimination of around-the-clock operating and maintenance personnel.

Figure 1-1 shows conditions of equal 20-year life cycle costs for HP-ICES and for conventional systems. If little or no waste heat is available from nearby industrial installations, high community energy density rates (corresponding to urban conditions) are required for economic viability of HP-ICES. If large amounts of waste heat are available, even relatively loosely built-up communities look promising provided the system is owned by the municipality. If the system is owned and operated by a share-holder owned public utility, either the community energy density must be high, or large quantities of waste heat must be available, or electricity and oil costs must escalate rapidly during the life of the system to assure economic competitiveness with conventional systems.

Table 1-1. Critical Parameters for HP-ICES Economic Viability

ADVANTAGEOUS	DISADVANTAGEOUS
Availability of large quantities of waste heat	No or little waste heat availability
High community energy density (urban)	Low community energy density (rural)
Both heating and cooling required during parts of the year	No heating required No cooling required
Integrated residential/commercial/industrial community	Residential community
Rapidly escalating fuel costs	Constant fuel costs
Municipal ownership	Utility ownership

Figure 1-1. Conditions of Equal Life Cycle Costs for HP-ICES and the Conventional System as a Function of Waste Heat Utilization, Community Energy Density, Energy Cost Escalation Rates, and HP-ICES Ownership

All HP-ICES use significantly less resource energy than conventional systems. For the baseline system analyzed, HP-ICES use 26% to 40% less resource energy than conventional systems during the heating season; at the times of the heating peak, the resource energy savings are 43% to 59%. Although there is no resource energy saving for the HP-ICES during the cooling season, it saves 19% during the peak cooling period. The annual resource energy saving for the HP-ICES is 22% to 34%. These savings are due to the lower requirements for electrical energy because, under all conditions, HP-ICES require more oil than conventional systems. The lower numbers in each case assume no waste heat, the higher numbers assume full waste heat utilization.

The HP-ICES concept analyzed in this report is based on a diesel powered central plant. The basic concept, however, is equally applicable to a central plant powered by prime movers fueled with less scarce energy sources, e.g., coal-fired steam turbines.

It is estimated that the HP-ICES concept is applicable to an average of 500 new communities to be constructed during the 1985-2000 period. The probable resource energy saving during that time period is 1.25×10^{15} Btu.

2. INTRODUCTION

The ever increasing scarcity of fossil fuel energy resources makes it imperative to conserve energy sources of all types. Since approximately one-quarter of the nation's energy is being used for space heating and cooling (Ref. 2-1), it is appropriate that a considerable effort be devoted to methods of reducing the consumption of non-replenishable energy sources employed to satisfy these needs.

Traditionally, Americans have aspired to living in single-family dwellings, or if they did not actually live in them, they aspired to living in them. Therefore, comfort heating and cooling requirements have usually been met by individual heating and cooling plants. This is in contrast to other countries where urban centers contain a larger fraction of the total population than in the U.S., and where apartments rather than single-family houses are the dominant dwelling unit. In many of those countries, district heating systems have been extensively used for years, and in a number of European countries, notable Sweden, Finland, and West Germany, district heating is being aggressively pursued as a matter of national policy.

This report discusses an integrated community energy system based on heat pump technology, herein referred to as HP-ICES. Such a system provides the heating and cooling requirements of a community by means of a common piping loop to which all HP-ICES users (buildings) are connected. Each user has a water source heat pump which heats or cools as required and extracts heat from, or rejects heat to, the common piping loop. A central plant maintains the water temperature in the common piping loop within the desired range. This report, the first in a series, covers the general concepts of HP-ICES for a typical community located in the Northeast, describes the engineering analysis of the central plant, the distribution loop, and the distributed heat pump installations,

evaluates technical and economic performance, addresses environmental implications, and discusses potential applications throughout the United States.

The principal author of the report is Richard E. Crane, Senior Research Engineer at the Franklin Research Center (FRC). Certain portions were written by Harold G. Lorsch and Michael A. Baker of FRC and by Robert G. Werden of Robert G. Werden and Associates. The writers are indebted to Mrs. Miriam Foster for the careful preparation of the manuscript.

3. DESCRIPTION OF THE HP-ICES CONCEPT

3.1 INTRODUCTION

Selection of the HP-ICES concept described in this report is predicated on our strong belief that the pioneering application of a novel community energy system should have as few unknowns as possible. For this reason we have developed an HP-ICES concept which uses proven design techniques and proven hardware elements.

Within a community there may be many building types, including single family residences, townhouses, small commercial buildings, motels, multi-family dwellings, and large commercial/industrial/institutional buildings. One possible community arrangement is shown in Figure 3-1. The HP-ICES concept presented here requires that the buildings within an HP-ICES community be interconnected with an underground distribution system of water mains. Only the primary distribution mains are shown in Figure 3-1. An illustration of the branch main piping for a residential area is shown in Figure 3-2. As shown in Figures 3-1 and 3-2, the HP-ICES primary and branch mains are distributed through the community in some logical network fashion to be reasonably convenient to the property lines of buildings in the community. The underground community HP-ICES mains would be placed in easements or public right-of-ways, whichever is most economical.

Figure 3-1 illustrates community HP-ICES mains as a two-pipe system. A single-pipe loop would require independent secondary pumping loops to be provided by each building owner to take heat from and return heat to the single pipe loop. Only the two-pipe system was evaluated in this study.

The proposed community HP-ICES loop would circulate water at not less than 60°F at peak winter conditions and not more than 95°F at peak

summer conditions. Each building would then extract energy from the loop for heating, or reject heat to the loop when the building was in the cooling mode. Each building would contain a water source heat pump which would use the loop as a heat source during the heating season and use the loop as a heat sink during the cooling season.

The proposed system also contains a central plant as shown in Figure 3-1. The central plant contains the necessary pumps to circulate water through the loop piping, and also contains equipment to either reduce the loop water temperature to 95°F (at peak summer conditions) or raise it to 60°F (at peak winter conditions).

In addition, along the loop waste process heat from industrial plants, utility plants, etc., could be interchanged into the loop in winter - from such plants as might be available in the community. An electric utility plant could provide most of such heat requirements in winter and, with the winter loop temperature only being at 60°F, it inherently permits heat exchange into the loop from most low level waste heat sources as well as the higher levels of waste heat obtainable from industrial plants or incinerators.

3.2 HP-ICES IN A REFERENCE COMMUNITY

The community shown in Figure 3-1 is called, for the purposes of this study, the reference community. This reference community was used to analyze the proposed HP-ICES concept in detail. The rationale used to create this community is described in Section 11.1. Information pertaining to the reference community is contained in Tables 3-1 and 3-2. Referring to Figure 3-1, the ICES central plant is located in the lower right-hand corner of the 856-acre site within the light manufacturing zoned area (33 acres). From the ICES central plant three main distribution piping branches lead out through the site. The peak heating and cooling loads fed by various distribution mains are shown in rectangular blocks on Figure 3-1. For example, the mains which proceed diagonally through the site have a total peak heating requirement of 32.5×10^6 Btu/hr and total peak cooling requirement of 38.2×10^6 Btu/hr as

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Figure 3-2. HP-ICES Branch Piping

Table 3-1. List of Buildings in Reference Community

	<u>Quantity</u>	<u>Average Density</u>	<u>Individual Building Area (ft²)</u>	<u>Total Building Area (ft²)</u>	<u>Gross Land Area (acres)</u>	<u>Population</u>
Single-family houses (2 stories)	1500	4/acre	1600	2,400,000	501.3	6,000
Townhouses (2 stories)	750	6/acre	1200	900,000	166.6	2,250
Low-rise apartments (2,3 stories)	750	12/acre	1000	750,000	83.3	1,750
Elementary School (1 story)	1	20%*		60,000	10.0	
Secondary School (1 story)	1	15%*		100,000	11.0	
Office Buildings 1 to 6 stories)		30%*		270,000	10.0	1,300
Light Manufacturing (1 story)		30%*		320,000	34.4	2,200
Commercial (1 story)		30%*		300,000	33.3	1,000
Churches	5		6000	30,000	3.3	
Recreation	5			30,000	3.3	
Streets (25% of gross area)					214.1	
TOTAL					856.5	10,000

*Percent of land covered by building

Table 3-2. Peak Heating and Cooling Loads for Reference Community

	Heating		Cooling	
	<u>10⁶ Btuh</u>	<u>%</u>	<u>10⁶ Btuh</u>	<u>%</u>
Single family (1-1/2 story average)	60.0	59.0	54.0	40.0
Townhouses	11.3	11.0	10.8	7.9
Apartments (2 story & 3 story)	8.3	8.2	9.4	6.9
Elementary School (1 story)	1.2	1.2	2.3	1.7
Intermediate/Secondary Schools (1 story)	1.8	1.8	3.8	2.8
Office Buildings (1 to 6 stories)	7.0	6.8	9.7	7.1
Light Manufacturing (1 story)	4.0	4.0	24.0	17.7
Commercial (1 story)	7.5	7.3	18.0	13.8
Churches	0.3	0.3	1.7	1.2
Recreation	0.3	0.3	1.7	1.2
TOTAL	101.7	100.0	135.4	100.0

indicated by the information above and to the right of the ICES central plant in Figure 3-1. Similarly, the main horizontal branch, across the bottom of the site, feeds a load equivalent to 32.2×10^6 Btu/hr peak heating and 22.4×10^6 Btu/hr peak cooling. The main distribution branch proceeding upward on the right side of the site feeds an aggregate load of 31.3×10^6 Btu/hr on the peak heating day and 21.8×10^6 Btu/hr on the peak cooling day. It would be impractical for this study to detail all of the water piping branch circuits in the 856-acre community. For costing purposes, the layout of a typical residential area was developed and is shown in Figure 3-2.

3.3 HP-ICES CENTRAL PLANT

3.3.1 Introduction

One or more HP-ICES central plants will be required to maintain the HP-ICES loop water temperature within the minimum and maximum temperature limits. During the winter, the supply water temperature to HP-ICES users will be approximately 60°F. In the summer, the loop supply water temperature will be prevented from exceeding 95°F. For the HP-ICES concept being described, it would be preferable to use waste heat during the winter to heat the HP-ICES piping loop. However, not all potential HP-ICES sites may have waste heat sources nearby, or the waste heat available may not be sufficient to meet the peak heating load. Where waste heat is not available or is not available in sufficient quantity to meet the peak heating load, the central plants would have diesel driven air-to-water heat pumps to supply the heat required by the HP-ICES loop in excess of that available from waste heat. During the summer, a cooling tower located at the central plant would be used to remove excess heat from the HP-ICES loop. The operation of the central plant is described in more detail in the following two subsections. For the HP-ICES concept being studied, the central plants will use diesel driven air-to-water heat pumps during the winter to heat the loop and a cooling tower during the summer to remove excess heat from the loop. The operation of the central plant is described in more detail in the following subsection.

3.3.2 HP-ICES Central Plant Operation - Heating

(Refer to Figure 3-3 and Table 3-3). This drawing shows the proposed HP-ICES central plant equipment. In the event that there was no available waste heat from industry to contribute heat to the ICES Loop System, several diesel driven air-to-water heat pump systems would be required. The drawing shows one diesel driven water-to-air heat pump system manifolded on the main loop piping. Loop water flows into and out of the refrigerant condenser (Item 14). In winter, approximately 50°F return loop water would flow in and out of Item 14 (refrigerant condenser) and then to the suction header of Item 16 (main loop water pump) to be returned to the community at approximately 60°F.

The centrifugal compressor (Item 1) rotating at a full load speed of about 5800 rpm, would be driven thru a speed increasing gear (Item 2) by a 1150 H.P. diesel engine (Item 3) developing this H.P. at 1200 rpm. The high pressure/high temperature discharge from the centrifugal compressor (Item 1) would discharge its vapor into the refrigerant condenser (Item 14), where it would condense its refrigerant, thereby giving up its latent heat of condensation to the main loop water and raising the loop water temperature from approximately 50°F to 58°F. The condensed refrigerant liquid would exit from the refrigerant condenser and pass thru the refrigerant liquid high pressure float control (Item 15), where its pressure and temperature would be reduced to a lower pressure and temperature level of minus 20°F on the 0°F day. This low temperature refrigerant liquid/vapor would then flow into the refrigerant low pressure receiver (Item 10). Here the refrigerant vapor would separate to the top of the receiver and the refrigerant liquid would be in the bottom half of the receiver. Low temperature refrigerant liquid exiting from the receiver (Item 10) would be pumped by the liquid refrigerant pumps (Item 11) out to and thru the several refrigerant outdoor coil banks (Item 12). Each outdoor coil bank would be served by a 50,000 cfm outdoor air fan and motor assembly (Item 13). As the 0°F outdoor air is discharged over the refrigerant outdoor coil bank (Item 12) the low temperature liquid refrigerant in the coil would be vaporized as it absorbs heat from the

Figure 3-3. Central Plant Equipment Diagram

TABLE 3-3
CENTRAL PLANT MAJOR EQUIPMENT

<u>Items Indicated</u>	<u>Other Items (Not Shown)</u>
1 - Centrifugal Refrigerant Compressor	24 - Air Compressor
2 - Speed Increasing Gear	25 - Air Receiver
3 - Compressor Diesel Engine Prime Mover	26 - Cooling Tower
4 - Exhaust Heat Recovery Unit	27 - Loop Water Strainers
5 - Exhaust Silencer	28 - Diesel Fuel Storage
6 - Exhaust Stack	
7 - Turbo Charger Heat Recovery Unit	
8 - Diesel/Loop Water Heat Exchanger	
9 - Diesel Heat Exchanger Pump	
10 - Refrigerant Low Pressure Receiver	
11 - Refrigerant Liquid Pump	
12 - Refrigerant Outdoor Coil Bank	
13 - Outdoor Air Fan & Motor Assembly	
14 - Refrigerant Condenser	
15 - Refrigerant Liquid H.P. Flow Control	
16 - Main Loop Water Pump	
17 - Main Loop Water Pump Diesel Prime Mover	
18 - Exhaust Heat Recovery Unit	
19 - Exhaust Silencer	
20 - Exhaust Stack	
21 - Turbo Charger Heat Recovery Unit	
22 - Diesel/Loop Water Heat Exchanger	
23 - Diesel/Heat Exchanger Pump	

outdoor air. Consequently, the return piping from the outdoor unit would carry back heat in the form of refrigerant vapor - and some un-evaporated liquid - to the refrigerant low pressure receiver (Item 10). Within the receiver (Item 10), the refrigerant vapor would collect at the top and unevaporated liquid would collect at the bottom to be returned to the refrigerant pumps. The refrigerant vapor at the top of the receiver (Item 10), (which carries the heat extracted from outdoor air), would be drawn to the compressor suction inlet (Item 1) to repeat the process.

The compressor prime mover diesel engine (Item 3) not only would impart heat of compression into the refrigerant compressor (Item 1) in the form of shaft horsepower, but also a major portion of its waste heat would be recovered in the diesel exhaust heat recovery unit (Item 4), from the engine cylinder jackets, and even from the turbocharger heat recovery unit (Item 7). All of this by-product waste heat would be recovered in a closed circuit loop pumped by the diesel heat exchanger pump (Item 9) thru the diesel/loop water heat exchanger (Item 8).

In Figure 3-3 it can be seen that, down-stream of the discharge of the main water loop pump (Item 16), a branch water line circulates some 60°F water thru the diesel/loop heat exchanger (Item 8) to pick up this engine waste heat and return it back into the suction of the main loop water pump (Item 16). Additional details are given in Section 3.8.

A similar branch water piping system is shown in Figure 3-3 to pick up the same equivalent of the engine waste heat from the 1800 rpm diesel engine (Item 17) which is the prime mover driving the main loop water pump (Item 16).

3.3.3 HP-ICES Central Plant Operation - Cooling

During the cooling season, the cooling tower would be used to cool the HP-ICES loop. The diesel engine driven main circulating pump would also be in operation, but the diesel driven heat pumps, if present, would be shut down for the season. Since the diesel driven heat pumps

would not be operating, the secondary heat recovery pump circuit would not be operated (Items 8 and 9 in Figure 3-3). However, the secondary heat recovery pump circuit connected to the main circulating pump diesel would be operated to cool the engine jacket and the supercharger. The pump engine heat would be transferred to the HP-ICES loop and then rejected to ambient by the cooling tower. The pump diesel exhaust gas heat recovery unit would be bypassed to avoid placing an unnecessary load on the cooling tower, see Section 3.8.

3.3.4 HP-ICES Central Plant Layout

(Refer to Figure 3-4). This drawing shows a suggested central plant layout for an HP-ICES designed to serve the reference community - if waste heat is available. The building is approximately 56' wide x 132' long and would be located in the industrial light manufacturing zoned area of the community. Based on 30% land coverage zoning, a 2.1 acre site would be recommended. The building would have large overhead doors on one side to accommodate long range "in and out" access for large equipment servicing, etc. Included in the building plan would be an office space for the chief engineer and his watch shift engineers, a small women's toilet room (for equal opportunity employment), a larger men's toilet and locker room, and a large tool and supply room. Clear head room within the building would be approximately 18'-0" to permit overhead piping above the equipment.

Shown in Figure 3-4 are four heat pump systems consisting of centrifugal heat pump units driven by diesel engines. Adequate space for pulling crankshafts and camshafts is shown.

Two main loop water pumps (P-1 and P-2) are shown, each driven by their respective diesel engine prime movers (with adequate space for pulling the camshafts and crankshafts for these two units). In the upper left-hand corner of Figure 3-4 there is shown a large air compressor and air receiver station to be used for cranking the several diesel engines during startup cycles.

Figure 3-4. Central Plant Layout

The HP-ICES loop cooling tower is located on the roof of the building (shown dotted above the four heat pump units). The cooling tower would be used to cool the HP-ICES water loop in the summer.

Located outside of the building (to the right on Figure 3-4) would be forty-eight outdoor air units, each consisting of a 100 square foot face area refrigerant coil, 50,000 cfm fan and motor assembly, and sheet metal shroud to direct the air from the fan ring into the 100 square foot face area of the refrigerant coil bank. Low pressure/low temperature refrigerant would be pumped by liquid refrigerant pumps (mounted on each heat pump unit in the engine room) outdoors thru refrigerant mains into each outdoor air unit refrigerant coil bank and then back to the equipment room and into the low pressure refrigerant receiver. Each outdoor air unit would be mounted on concrete piers, elevated approximately one foot above grade, making the total height silhouette of each outdoor air unit approximately 11' high x 10' wide x 3' deep (direction of air flow). It can be seen that air flow of the colder air discharge from typical outdoor air units opposes each flow. This will minimize by-passing of cold air back into the suction of each outdoor air unit to prevent degradation of the heat source of the outdoor air.

In the event that the community could provide a significant amount of waste heat to the loop from industry, fewer heat pump units with their associated battery of outdoor air units would be needed. Then the building would be smaller, and the land coverage at the rear of the building would be reduced. However, the building still would have to house the main loop water pumps (P-1 and P-2), the air compressor, support the cooling tower, and house two 400 H.P. low pressure steam boilers and steam-to-water exchangers to provide for emergency back-up on the coldest day in the event the community waste heat was not available to the loop due to industrial strikes, shutdowns, etc. Similarly, in the event that the community could normally provide 100% of the loop heat requirements from industrial waste heat, no heat pump units would be needed in the building. But two 800 H.P. boilers would be required with a steam-to-water heat exchanger for emergency back-up.

Not shown in the plant layout, but implied, are outdoor underground diesel fuel storage tanks. In the case of the two alternative plant layouts, additional underground storage tanks would be required for emergence boiler fuel (probably #4 and #5 oil).

3.4 HP-ICES USER HEAT PUMP SYSTEMS

Depending on the size of the user's premises, any one of three configurations of heat pumps may be used. The three heat pump configurations, referred to as Types A, B, and C, are shown in Figures 3-5, 3-6, and 3-7. It can be seen that the HP-ICES loop is connected directly to the user heat pumps. No heat exchanger interface is required because the temperatures and pressures in the HP-ICES loop are compatible with the water cooled condensers and evaporators of commercial heat pumps.

3.4.1 Type A User Heat Pumps

Type A heat pumps (refer to Figure 3-5) would be used in single family residences, townhouses, condominium apartments and leased apartments. These are factory assembled package water source heat pumps available from many manufacturers in various capacities. Each unit would consist of a reversible cycle heat pump containing a reciprocating compressor (generally employing R-22 refrigerant), an indoor coil and centrifugal fan (labeled as a duct mounted coil in Figure 3-5), a combination water cooled condenser/evaporator, four-way refrigerant reversing valve, piping and controls, all within a factory assembled chassis and casing.

The heat pump can provide heating or cooling depending on the positioning of the 4-way valve. In the heating mode, heat is extracted from the HP-ICES loop in the condenser/evaporator, and air from the conditioned space is heated as it passes through the duct mounted coil. In the cooling mode, the operation of the duct coil and the condenser/evaporator is reversed. Heat is removed from the conditioned space at the duct mounted coil and rejected to the HP-ICES loop at the condenser/evaporator.

Figure 3-5. Type A HP-ICES User Heat Pump

3.4.2 Type B User Heat Pumps

Type B heat pumps would be used in medium size commercial/industrial and institutional buildings. The type B heat pump (refer to Figure 3-6) is a factory assembled water source heat pump currently customized on special order from several manufacturers. It would consist of a pre-assembled and piped unit mounted on a structural steel bed plate and would include one or more reciprocating compressors with motors and starters, a double bundle condenser, double bundle chiller, piping and controls.

Type B heat pumps can supply heating, cooling, or simultaneous heating and cooling. When the unit is in the heating mode, the three-way HP-ICES loop water valve is positioned to permit the flow of loop water through the double bundle chiller. The loop water is cooled from approximately 60°F to 50°F as it passes through the double bundle chiller. The heat extracted from the HP-ICES loop is discharged from the double bundle condenser to the heating system water loop. The chiller tube bundle and condenser tube bundle used during the heating mode are normally referred to as the winter bundles.

The type B heat pump is unidirectional (nonreversing refrigerant) so the refrigerant flow is identical in the heating or cooling mode. However, for cooling, the three-way valve is positioned so HP-ICES loop water flows through the double bundle condenser. Energy extracted from the building's chilled water system in the double bundle chiller is rejected to the HP-ICES loop water in the condenser. In the cooling mode, the double bundles employed in the chiller and condenser are commonly referred to as the summer bundles.

The type B heat pump can supply simultaneous heating and cooling. When the building cooling load exceeds the building heating load, the excess heat is rejected to the HP-ICES loop through the condenser summer bundle. Conversely, if the heating load exceeds the cooling load, the additional heat required is extracted from the HP-ICES loop by the chiller winter bundle.

Figure 3-6. Type B HP-ICES User Heat Pump

3.4.3 Type C User Heat Pumps

Type C heat pumps would be used in large commercial, industrial and institutional buildings. This system (refer to Figure 3-7) is very similar to the type B heat pump, except that centrifugal rather than reciprocating compressors are used along with high pressure float regulators instead of thermal expansion valves. Systems of this type are available on special order from several manufacturers. The operation in the heating, cooling, or simultaneous heating and cooling modes is the same as for type B heat pumps.

3.5 HP-ICES OWNERSHIP

Three types of HP-ICES ownership were considered in this study including ownership by a private corporation, cooperative ownership by the users, and municipal ownership. Although all three types of ownership are economically feasible, it is shown in Section 6 of this report that a municipally owned HP-ICES has a significantly lower life cycle cost than HP-ICES with the other two types of ownership.

The owner of HP-ICES would own the central plant and loop piping and might or might not own the user heat pumps. If all the HP-ICES users were tenants rather than building owners, then the HP-ICES owner would most likely own the building heat pump systems and would be responsible for their operation and maintenance. However, if the buildings are owner occupied, it's doubtful the HP-ICES central plant and piping loop owner would want to own the building systems. As owner, he would be responsible for their operation and maintenance but might not have full control over the equipment. Also, he would have to have free access to the buildings. On the other hand, it would be advantageous to a building owner to supply his own equipment since it would give him more flexibility to tailor the arrangement of the equipment and the air side distribution system to suit his needs. Consequently, if the HP-ICES community consists of owner occupied buildings, it's unlikely that the HP-ICES central system (plant and piping) will also own the user equipment.

Figure 3-7. Type C HP-ICES User Heat Pump

3.6 BASIS FOR CUSTOMER CHARGING

The owner of the HP-ICES system must be able to recover his costs by charging the customers for the service supplied. Specifically, the customer should be charged according to the amount of heat extracted from the HP-ICES loop during the winter and rejected to the loop during the summer. Additionally, customers which reject heat to the loop during the winter should receive a credit because this reject heat reduces the load on the central plant.

The most equitable method of determining customer charges would be to use Btu meters to measure the flow of energy to and from the HP-ICES loop for each service connection. Also, it has been found that individual metering has a significant impact on energy consumption. It has been found in Sweden that individual metering of apartments reduces energy use by up to 25% (Ref. 3-1). Several Btu meters are now on the market, but they do not totally meet the requirements of this HP-ICES. These meters usually consist of a flow measuring device, two temperature sensors, and a mechanical or electrical integrator/totalizer. For the HP-ICES user, a temperature sensor would be located in the inlet and the outlet connection to the HP-ICES loop. The meter could be located in the inlet or outlet connection.

The presently available Btu meters are designed to measure energy flow in one direction only. If the direction of energy flow reverses, as would happen with this HP-ICES when a user heat pump switches between heating and cooling modes, most of the meters now available would run backwards. This would lead to a reading of zero if the heat extracted from the HP-ICES loop was equal to the heat rejected to the loop between meter readings. This problem could be solved by using a separate meter to measure heat flow to and from an HP-ICES user as long as the meters are designed so they cannot run backwards. However, the cost would be high.

A Btu meter, model 2755 made by the Bristol Instruments Company, is now on the market which could be modified to meet the needs of this

HP-ICES. The meter consists of an orifice plate and pressure transducer to measure flow, two temperature sensors and a totalizer, and the cost is \$2500. For an additional \$300 the meter could be modified to read energy flows in two directions by adding a second totalizer and by making minor changes in the electronics (Ref. 3-2). A cost of \$2800 per meter is acceptable for commercial and industrial users, but is excessive for residential use. The meter cost would be higher than the residential heat pump cost.

The high Btu meter cost is due in part to the relatively low number of these units sold in the U.S. as compared to other countries where district heating is more prevalent. In Sweden, for example, Btu meters for single family detached houses can be installed for the equivalent of 300 U.S. dollars (Ref. 3-1). If HP-ICES is implemented to a significant extent in the U.S., it is expected that meter costs will be reduced markedly.

The Btu meters discussed above are the type normally used in district heating systems. Because normal operation of district heating systems may involve adjustment of the system flow rate, each Btu meter must have a flow measuring device. However, in this HP-ICES system the flow rate will not be adjusted intentionally, therefore, it may not be necessary for the Btu meters to have a flow measuring device, since loop water will always be flowing through the user equipment. In this case, a relatively simple Btu meter consisting of two temperature sensors and an electronics package could be used. The user flow rate would only have to be measured once, and the Btu meter adjusted to give correct readings based on that flow rate. However, the effect of the addition of new users or additional piping mains on the flow distribution with the piping loop and user flow rates would have to be determined and accounted for when determining customer charges.

Since the feasibility of this simplified Btu meter has not been demonstrated yet, it was assumed that the presently available meters, due to their expense, would only be used for commercial and industrial

users. Residential users would be charged a flat fee which would vary with the time of year. This lack of suitable low cost residential meters will not have a significant impact on HP-ICES implementation since it is shown later in Section 6 of this report that communities which are predominately residential are not particularly good HP-ICES sites.

3.7 WASTE HEAT RECOVERY

The use of waste heat by HP-ICES has a significant impact on the economic feasibility of this concept because of reduced capital and operating costs. Waste heat could be recovered from many industrial processes and could be in the form of a hot liquid or gas prior to recovery.

The recovery of waste heat from a hot gas stream requires the installation of a heat exchanger at the industrial process and piping to transport the recovered waste heat to the HP-ICES loop. If the waste heat is recovered from a liquid stream, the heat exchanger could be located at the process site, or the waste heat source could be piped to a heat exchanger connected directly to the HP-ICES loop.

The piping and waste heat recovery heat exchanger could be owned by either the HP-ICES owner or the waste heat supplier. The HP-ICES owner might want control over the equipment to protect the integrity of the HP-ICES loop; however, the waste heat supplier would be just as concerned about a disruption of the industrial process supplying the waste heat and would therefore also be concerned that the heat recovery equipment was properly maintained. For the purposes of this study, it was assumed that the HP-ICES owner would own the waste heat recovery equipment.

Waste heat recovery is discussed further in Section 9 of this report, and heat exchanger costs are given.

3.8 DIESEL ENGINE HEAT RECOVERY EQUIPMENT

The basic operation of the diesel engine heat recovery equipment has been discussed previously. Here, the operation of this equipment is discussed in more detail.

The main circulating pump and heat pump diesel engine heat recovery equipment is shown in Figure 3-3. Table 3-3 identifies the equipment in Figure 3-3. It can be seen in Figure 3-3 that HP-ICES loop water is taken from the discharge side of the main loop water pump (Item 16) and passed through diesel/loop water heat exchangers (Items 8 and 22). Such an arrangement could cause flow balancing problems if not properly designed. This potential problem could be eliminated by installing another heat exchanger between the HP-ICES loop and the secondary heat recovery loop; however, it is not felt this added precaution is necessary. The flow through the diesel/loop water heat exchangers (Items 8 and 22) will be constant throughout the year even when the diesel driven heat pump (Item 3) is inoperative during the cooling season. Because the flow is constant, balancing valves (not shown in Figure 3-3) can be adjusted during system startup to maintain the desired flow distribution.

The diesel engine heat recovery equipment shown in Figure 3-3 was included in this HP-ICES concept to maximize the efficiency with which the central plant uses fuel oil. The economic feasibility of this equipment was not investigated. Since the diesel engines do require a cooling system, the savings achieved by eliminating the standard cooling system will offset part of the waste heat recovery equipment cost.

The temperature rise of the HP-ICES loop water passing through the central plant during the heating season will be approximately 10°F. The percentage of the total heat added to the HP-ICES loop by various central plant components during the peak heating period is shown in Table 3-4. It can be seen in Table 3-4 that diesel engine waste heat represents an appreciable fraction of the total heat added to the loop. Since the total temperature rise is only 10°F, the temperature rise due to the diesel engine heat recovery equipment is small but, due to the large flow rates involved, the energy added to the HP-ICES loop is significant.

Table 3-4. Percentage of Total Heat Added to HP-ICES Loop by Central Plant Equipment During the Peak Heating Period

Equipment	Percentage of Heat Added to Loop
Main Condensers	72.17
Main Circulating Pump	1.67
Main Circulating Pump Diesel Heat Recovery Equipment	2.43
Compressor Diesel Heat Recovery Equipment	23.73

3.9 DEFROSTING OF CENTRAL PLANT HEAT PUMP

The common air-to-air, mass produced, residential heat pump encounters an operating penalty due to evaporator frosting when operating under high relative humidity conditions at 32°F to 40°F ambient dry bulb temperatures. Such units require reversing the cycle for defrosting of the evaporator coil, thereby temporarily cooling the interior space removal of heat, introduction of expensive resistance heating, or a combination of both, thereby degrading the heat pump COP (Coefficient of Performance). Such performance drawbacks are inherent in equipment designed to sell in a competitive marketplace to home builders who pass through such products to an unsophisticated consumer market. Many such units are defrosted on a time cycle triggered by temperature.

A better, though more expensive, method is demand defrost, which only initiates defrost cycles when needed and only for the minimal time required to accomplish defrost. Table 3-5 shows the differences in the number of defrost cycles per day for timed defrost and demand defrost.

Central plant heat pumps operate on demand defrost which drastically reduces the defrost cycles from timed defrost. Moreover, a modular HP

Table 3-5. Typical Defrost Cycles Per Day

Ambient Dry Bulb Temperature	%Relative Humidity	TIMED DEFROST			Demand Defrost
		Timer Interval			
		30 min	60 min	90 min	
40	100	48	24	16	30
40	80	48	24	16	10
40	60	48	24	16	4
30	100	48	24	16	24
30	80	48	24	16	8
30	60	48	24	16	4
20	100	48	24	16	14
20	80	48	24	16	7
20	60	48	24	16	3
10	100	48	24	16	8
10	80	48	24	16	5
10	60	48	24	16	2
0	100	48	24	16	5
0	80	48	24	16	3
0	60	48	24	16	2

From: Trane Co. Catalog S-PKGP-1, June 1978

plant like the one described here has the capability of reducing coil frosting through variations in operating conditions. One of these is compressor unloading which can easily be accomplished in the diesel driven centrifugal heat pump by reducing the speed of the prime mover. This raises the refrigerant evaporating temperature and significantly decreases the frosting rate. Since the central plant is designed to provide the required loop heat at below-freezing temperatures, it has sufficient capacity in the 32°F to 40°F range to permit partial unloading. Such an operating mode is not provided by the constant speed residential heat pump which handles partial loads by on-off cycling with unnecessarily low evaporator temperatures that promote coil frosting.

The successful performance of major air source heat pump installations designed by Werden Associates is proven by many years of operation to the owners' full satisfaction. Observations on such installations show less than 1 percent defrosting during operation in the 32°F to 42°F regime. Therefore, the effect of defrosting operation on the COP of central HP plants is below the accuracy of the analysis shown in Section 11, and it has not been explicitly calculated.

4. HP-ICES APPLICATION POTENTIAL

4.1 INTRODUCTION

The HP-ICES concept described in this report can have a significant impact on resource energy consumption as compared to space conditioning systems now in use. However, this HP-ICES is not applicable to all communities or to all areas of the nation. The potential of this HP-ICES concept to conserve energy, factors affecting its applicability, and the potential market for this concept are discussed in this section of the report.

4.2 FACTORS AFFECTING HP-ICES IMPLEMENTATION

Several factors have been identified which can have a major effect on the implementation of this HP-ICES concept. These factors are:

- Community characteristics
- Climate
- Resource requirements
- System availability and reliability
- Economic conditions.

These factors are discussed separately in the following subsections.

4.2.1 Community Characteristics

The mix of building types in a community can have a significant effect on HP-ICES feasibility. An advantage of the HP-ICES being investigated is that reject heat from buildings in the cooling mode can be transferred through the HP-ICES loop to buildings requiring heating. By transferring heat from one building to another, central plant energy use and possibly its required peak capacity are reduced and resource energy

is saved. Communities which have well developed light manufacturing and commercial sectors will benefit more from HP-ICES than "bedroom" communities. Light manufacturing and commercial buildings have higher internal loads than residential structures and have more cooling hours per year, thereby increasing the potential for simultaneous heating and cooling within the community. The presence of a sizeable light manufacturing center may also improve HP-ICES performance by supplying waste heat to the loop. Urban centers with high use office buildings can benefit from HP-ICES because the interior cores of these buildings often require cooling year around. Using a type C heat pump system as described in Section 3, the interior heat gains of high use buildings could be transferred to the building perimeter areas when heating is required. If the interior gains exceed the perimeter heating requirements, or if no perimeter heating is required, the excess heat could be rejected to the HP-ICES loop for use by another HP-ICES user and would reduce the heat demand as seen by the HP-ICES central plant.

The mix of building types is only one of several factors which can affect HP-ICES viability. In order to determine the potential for HP-ICES, it was necessary to establish the characteristics of a good HP-ICES site. Thermal and economic analyses were performed for HP-ICES in the reference community. Then a sensitivity analysis was performed to determine how changes in the composition of the reference community and variations in economic parameters would affect HP-ICES application potential. The sensitivity of HP-ICES viability was examined with respect to the percentage of waste heat available relative to the peak heat demand, the type of ownership (i.e., privately owned utility, community cooperative, or municipal utility), community size, community energy density based on peak heating demand, energy cost escalation rates, and the annual salary of the central plant operating staff. The thermal analysis is described in Section 5, and the economic analysis and sensitivity analysis are described in Section 6.

Figure 4-1. Conditions of Equal Life Cycle Costs for HP-ICES and the Conventional System as a Function of Waste Heat Utilization, Community Energy Density, Energy Cost Escalation Rates, and HP-ICES Ownership

It was determined that community size has a negligible effect on HP-ICES viability as shown in Figure 6-2. Since the type B and C heat pump systems described in Section 3 are essentially small versions of HP-ICES, an HP-ICES site could consist of only one building. Conversely, there is no limit to the size of an HP-ICES site. If an HP-ICES of a given size is viable, it would be possible to construct a viable HP-ICES of twice the size, assuming the composition of the community remains the same, by building a second HP-ICES identical to the first and inter-connecting the two. The conclusion that HP-ICES size does not affect its economic feasibility is based on the assumption that the owner can raise the required capital. The higher initial cost for HP-ICES as compared to the conventional alternative will limit the size of HP-ICES.

Although HP-ICES economic feasibility is not very sensitive to community size, it is sensitive to other factors. In particular, community energy density, type of ownership, percent waste heat utilization, and energy cost escalation rates. The effect of these factors on HP-ICES viability is shown in Figure 4-1. Figure 4-1 was created using the results of the sensitivity analyses mentioned previously. Figure 4-1 shows conditions of equal life cycle costs for HP-ICES and the conventional system as a function of the factors mentioned above.

It can be seen from Figure 4-1 that HP-ICES benefits from municipal ownership, higher energy cost escalation rates, higher community energy densities, and greater percentages of waste heat availability. For a specific type of ownership and fixed set of energy cost escalation rates, an increase in waste heat availability will make HP-ICES feasible in communities with lower energy densities.

The energy densities of various sectors of a community have been identified (Ref. 4-1) and are shown in Table 4-1. The energy densities shown in Table 4-1 are lower than those given in Ref. 4-1 by a factor of 0.895 since it was assumed that the densities given in Ref. 4-1 were based on zoned area whereas the energy densities used in the sensitivity analysis were based on gross community area (refer to Table 3-1 for a

Table 4-1. Community Energy Densities

Energy Density Based on Peak Heating Demand (10 ⁶ Btuh/Acre)	Community Description
Over 0.97	Urban Center-High Rise Buildings
0.87 - 0.63	Urban Center-Multistoried Buildings
0.63 - 0.25	Urban Center-Commercial Buildings and Multifamily Apartment Buildings
0.25 - 0.15	Residential Area-Town Houses
less than 0.15	Single Family Detached Houses

comparison between zoned and gross area). Using Table 4-1 and Figure 4-1, conclusions can be drawn as to acceptable HP-ICES communities. HP-ICES will be able to achieve a greater impact on the nation's energy consumption if it is not limited to sites such as urban centers with high energy densities. If HP-ICES is a municipal utility, it would be feasible in a predominantly residential community, such as the reference community, if a major source of waste heat is available (i.e., 90% of the peak heat demand assuming the lowest set of energy cost escalation rates apply). At higher energy cost escalation rates, HP-ICES in a residential community would be less dependent on the availability of waste heat to achieve economic viability. As a community becomes less residential (i.e., more developed), HP-ICES economic feasibility is less dependent on waste heat availability.

It has been stated several times that HP-ICES benefits from the use of waste heat and it has been shown that waste heat availability can have a significant affect on HP-ICES application potential. Therefore it would be worthwhile to discuss the potential for finding waste heat sources in various types of communities. Urban centers with high rise office buildings have high energy densities. Depending on the type of HP-ICES ownership and the energy cost escalation rates, it can be seen in Figure 4-1 that the percent waste heat utilization required for HP-ICES viability ranges from 0% to 70%. While it is possible that some waste heat sources may be found in a dense urban center, it is more probable that such heat sources would be located in less dense areas, and waste heat would have to be piped from the source to the HP-ICES site. Major waste heat sources would more likely be found close to urban centers in older cities.

There are several types of industries which are often found near areas zoned as commercial/residential (communities with energy densities in the range of 0.63-0.25 as shown in Table 4-1) including rubber processing, meat packing and auto parts rebuilding plants. Individually, these plants may not be able to meet the HP-ICES waste heat demands, however, several such plants collectively could make HP-ICES viable.

Residential areas are the least attractive HP-ICES sites. To be viable, waste heat availability is a necessity, and municipal ownership and high energy cost escalation rates are also advantageous. Since large waste heat producers such as paper and steel mills and chemical plants, etc. tend to locate away from urban centers, it is possible that residential communities in the vicinity of such plants could employ HP-ICES effectively.

4.2.2 Climate Implications

The thermal performance of HP-ICES was analyzed using weather data for Philadelphia, PA. (5000 degree-days) and it was found that this system uses significantly less resource energy than the conventional alternative. Although the thermal performance of HP-ICES was not analyzed for other climatic regions, based on the estimated performance in Philadelphia and the nature of the system, several comments can be made as to the effect of climate on HP-ICES applicability.

The thermal performance advantage of HP-ICES relative to the conventional system is significant during the heating season and marginal during the cooling season. Consequently HP-ICES is not attractive in regions where little or no heating is required. Possibly the HP-ICES concept could be modified to function as a cooling-ICES but this was not investigated.

If the central plant uses air source heat pumps to heat the HP-ICES loop, the system performance in very cold climates would suffer, because the COP of air source heat pumps decreases as the ambient temperature decreases. However, by using waste heat in place of air source heat pumps, HP-ICES could function effectively in cold climates, and its performance advantage over the conventional alternative would be greater than in milder climates because the benefits of HP-ICES operation occur mainly during the heating season.

Since there are very few areas in the U.S. that require no heating, and HP-ICES can function well in very cold climates, it appears that climatic conditions will not significantly impair HP-ICES application potential.

4.2.3 Effect of Resource Requirements

The resources required to construct an HP-ICES are essentially, steel, concrete and other building materials and the energy required to make them, plus fuel for the construction equipment and labor. An energy payback period was not calculated for HP-ICES, but it should not be very long. As compared to the conventional system, the HP-ICES variations can reduce resource energy consumption by 24% to 40% per year. The materials required to construct HP-ICES are not particularly scarce, so their availability should not affect HP-ICES implementation. A beneficial side effect of HP-ICES will be the creation of new jobs during the construction phase.

The HP-ICES being discussed consumes fuel oil and thus depends on a scarce energy resource. By utilizing waste heat to a significant extent, however, HP-ICES will consume less oil than the conventional alternative. This may limit the use of HP-ICES to sites where waste heat is available, because better uses can be found for oil than to operate space conditioning equipment. If, at some time in the future, oil is no longer available for use by space conditioning systems due to legal or economic restrictions or just lack of supply, this HP-ICES concept can be modified to use other energy sources. The diesel prime movers could be replaced with motors powered by electricity from nuclear or coal fired power plants or by steam driven turbines powered by an on-site coal fired boiler.

4.2.4 System Availability and Reliability

The HP-ICES availability and reliability will not be a limiting factor in HP-ICES acceptance. While the chance of system failures cannot be totally eliminated, the equipment used would be chosen for its reliability and would receive adequate preventive maintenance. Redundant systems would be available when equipment failures did occur. The availability and reliability of the diesel prime movers, for example, are excellent. These diesel engines would be rated for continuous duty, but would not be run continuously. During the summer, the heat pump diesel engines would be idle, allowing sufficient time for any maintenance required. It has been assumed that at least one watch engineer would be on duty in the central plant at all times and he was factored into the cost estimate.

The need for full time supervision at the central plant is not a prerequisite. Total energy plants, similar in concept to HP-ICES, have been designed to operate without full time supervision. This could also be done for HP-ICES. However, full time supervision increases HP-ICES reliability, and the added cost over the life of the system is only 1% to 3%. Thus, the HP-ICES would tend to have the same reliability as a public utility.

4.2.5 Economic Conditions

Economic conditions will be a significant limiting factor affecting HP-ICES implementation. The initial cost is much higher than that of the conventional system, consequently a developer must be of sufficient size before he can raise the required capital. To undertake a project of this type, the developer must be certain that he will recover his investment in a reasonable period of time. High interest rates will increase the investment recovery time. Economic incentives such as tax relief may be required to make the HP-ICES concept economically feasible.

4.3 POTENTIAL APPLICATIONS

The characteristics of an acceptable HP-ICES community were discussed in Section 4.2.1. There are many existing communities which meet the basic requirements for an acceptable HP-ICES site; however, in most cases, the implementation of HP-ICES is doubtful. The disadvantages of installing HP-ICES in existing communities include the high cost of installing pipe under paved streets and the requirement that existing space conditioning equipment be modified or replaced. This does not mean the implementation of HP-ICES in existing communities is totally impractical, but that in most cases the economics will not be as favorable as in a new community. An exception might be a city embarking on a major urban renewal project. If buildings are being replaced, the installation of the required HP-ICES user heat pump equipment would not impede HP-ICES acceptance since the installed cost would be lower than for the conventional alternative. Or, if buildings are just being refurbished, it still might be possible to convert existing equipment to type B or C heat pumps as described in Section 3. If the urban renewal project is extensive, it may include excavation of streets for the installation of new utilities, in which case the cost of the excavation and repaving could be shared by the parties involved including the HP-ICES system.

Because of the potentially strong impediments to the installation of HP-ICES in existing communities and a lack of sufficient information to determine the number of existing cities that might be acceptable HP-ICES sites, the potential applications for this concept were limited to an estimation of its use in new communities.

The completely integrated "new town" concept which was popular in the past is no longer being implemented. The Department of Housing and Urban Development Title 7 projects which fit the "new town" category have ceased operation for economic reasons. No new ones are being planned at this time. Typical new residential developments now under construction have 500 to 1000 houses. Architects and planners who were

interviewed were unable to cite exact numbers of such developments that are started each year. Estimates ranged from less than one-hundred to several hundreds.

Developments in this size range will usually attract commercial establishments such as retail stores and shopping centers as the community grows, schools will have to be built, and an industrial park may locate nearby. Thus, these developments which are predominately residential at the start may, as they grow, become attractive sites for HP-ICES.

It is estimated that HP-ICES will not have a major impact on the nation's energy consumption before 1985. It is unlikely that developers will commit themselves to using HP-ICES until demonstration units are constructed and operating results are obtained. Further, it will take two years or more from the start of construction until an HP-ICES is on line. No new technology with the high capital cost associated with HP-ICES will achieve immediate acceptance, and the building industry does not adapt quickly to new ideas and concepts.

The cumulative energy savings possible with HP-ICES by the year 2000 were estimated assuming the initial systems became operational in 1985. It was also assumed that an average of 500 developments in the 500 to 1000 residential unit size range (750 average) will be initiated each year between 1985 and 2000, and that all of these developments would apply the HP-ICES concept. In other words, 375,000 new dwelling units each year will be served by HP-ICES, and 5.6×10^6 dwelling units will be using HP-ICES by the year 2000.

Based on present (1978) conditions, this number may appear high. However, one must realize that the ever increasing energy shortage (whether manifesting itself in reduced quantities available or in increased prices or in both) expected to occur between 1978 and the year 2000 will cause changes in housing construction. While the single-family dwelling is still the goal of most US citizens and will probably remain

so, sharply increasing costs of real estate and energy will make this goal more difficult to achieve for the majority of families. Community residential developments offer a way of reducing real estate costs as well as energy costs. It can, therefore, be expected that these developments will become increasingly popular during the time span under consideration due to purely economic forces. If one adds the advantages of scarce resource energy conservation which the ICES concept permits, it is probable that government regulations will encourage the construction of this type of community. In the light of these considerations, the assumption of an average annual increase of 375,000 dwelling units for HP-ICES does not seem to be unduly optimistic.

The resource energy consumption by the reference community HP-ICES is 277.8×10^9 Btu/yr. The conventional system resource energy usage is 356.2×10^9 Btu/yr.* The resource energy saved by HP-ICES is therefore 78.4×10^9 Btu/yr and the reference community which has 3000 dwelling units saves 26×10^6 Btu of resource energy per year per dwelling unit. Based on the assumptions that 375,000 new dwelling units per year would employ HP-ICES and also assuming that the annual average energy saving for each unit in the country is the same as for each unit in the reference community analyzed, HP-ICES would save 1.1×10^{15} Btu of resource energy by the year 2000.

This estimate of energy savings due to HP-ICES is for a system with no waste heat utilization. If all HP-ICES were able to utilize waste heat to the fullest extent, the resource energy savings by the year 2000 would increase to 1.7×10^{15} Btu. It does not appear likely that all HP-ICES will utilize 100% waste heat; however, comparing the last two figures one would conclude that a resource energy saving of 1.25×10^{15} Btu is not unreasonable.

*See Table 5-4.

5. HP-ICES ENERGY UTILIZATION

5.1 INTRODUCTION

The annual and peak load performance of the HP-ICES and the conventional alternative for the reference community are described in this section. The methodology used to determine energy use by the various building types in the reference community and HP-ICES central plant performance factors are discussed in Section 11. The term conventional system actually encompasses several different heating and cooling systems commonly used at the present time. The conventional system(s) assumed to be used by the various building types in the reference community are shown in Table 5-1.

Table 5-1. Conventional System

<u>Building Type</u>	<u>Heating/Cooling System</u>
Single-family House and Townhouse	Air-to-air heat pump with resistance auxiliary
Apartments	Electric resistance heaters/ packaged "through-the-wall" air conditioners
Offices, Light Manufacturing, Commercial, Schools, Churches, Recreation Centers	Oil fired boiler/central air conditioning system

The choice of the heating/cooling system for the apartments shown in Table 5-1 could also have been an oil fired boiler/central air conditioning system. The system shown in Table 5-1 was chosen because the installed cost is much lower than for a central system the heating/cooling system average costs for apartments as given in Reference 5-1 are much lower than for other building types, therefore it was assumed that apartment buildings employ low first cost systems such as the type shown in Table 5-1.

The results of the thermal analysis are presented in three sections. First the results of a thermodynamic first law analysis are discussed, then the results of a thermodynamic second law analysis, and finally the magnitude of resource energy saving possible with HP-ICES is presented.

5.2 FIRST LAW ANALYSIS

The first law thermal performance of the conventional system and HP-ICES is shown in Figures 5-1 through 5-14. All energy values are shown per unit of resource energy consumed.

The boundaries of the conventional system and HP-ICES are shown by a dashed line. Efficiencies and performance factors are shown for the various types of equipment.

The efficiency of equipment such as space heating boilers, electric resistance heaters and the electric power plant is indicated by an " η ." Heat pump and HP-ICES central plant performance is indicated by a seasonal performance factor (SPF) for annual heating or cooling mode performance and by a performance factor (PF) for peak mode performance. The performance factors are analogous to a coefficient of performance and are equal to the ratio of the useful output divided by the purchased energy input. The efficiencies and performance factors shown for the power plant and conventional system equipment are estimated values but are felt to be representative of the performance of this type of equipment.

The performance factors shown for HP-ICES user equipment represent the weighted average of the performance factors for the residential and commercial equipment in the HP-ICES. The performance factors for residential equipment were determined based on an average of the performance data for three sizes of heat pump as given in Ref. 5-2. The performance factors for commercial/industrial HP-ICES users were based on the average performance of heat pumps in the 50 ton to 300 ton size range as given in Ref. 5-3. It was assumed that, whenever HP-ICES

user equipment was in the heating mode, the HP-ICES loop temperature was 60°F. Similarly, during the cooling season, the loop supply temperature was assumed to be 95°F. The HP-ICES user equipment performance factors are based on these values.

The performance factors shown for the HP-ICES central plant were calculated as the ratio of the heat added to the HP-ICES loop (heating season) or heat extracted from the loop (cooling season) divided by the total purchased energy input. Thus the central plant performance factors include the energy used to run the main circulation pumps, air source heat pumps (if used), air source heat pump outdoor fans and the cooling tower fans.

Figures 5-1 through 5-4 show the annual heating performance of the conventional system and HP-ICES with 0%, 50% and 100% waste heat utilization, respectively. The total heating loads per unit of resource energy consumed are shown in the block labelled conditioned space. It can be seen in Figures 5-1 through 5-4 that all HP-ICES can supply a greater load per unit of resource energy consumed than the conventional system and that increased waste heat utilization benefits HP-ICES.

By taking the ratio of the load supplied by the conventional system in Figure 5-1 to the loads supplied by HP-ICES in Figures 5-2 through 5-4 and multiplying these ratios by electricity consumption and oil consumption of the respective HP-ICES, it can be shown that all HP-ICES consume less electricity than the conventional system, and HP-ICES utilizing waste heat require less fuel oil than the conventional system.

No performance factor is shown for the central plant in Figure 5-4 because, with 100% waste heat utilization, there are no air source heat pumps in the central plant. The only equipment in operation is the diesel driven main circulating pump.

It can be seen in Figures 5-2 and 5-3 that the central plant performance factor decreases when waste heat is utilized. If waste heat cannot supply the entire peak heating demand, the difference is supplied

Figure 5-1.

Normalized Energy Balance Diagram
Conventional System Annual Performance - Heating Mode

Figure 5-2. Normalized Energy Balance Diagram
HP-ICES Annual Performance - Heating Mode
0% Waste Heat

Figure 5-3.

Normalized Energy Balance Diagram
 HP-ICES Annual Performance - Heating Mode
 50% Waste Heat

Figure 5-4.

Normalized Energy Balance Diagram
 HP-ICES Annual Performance - Heating Mode
 100% Waste Heat

by the diesel driven air source heat pumps. During the mild portions of the heating season, waste heat supplies all of the HP-ICES heat demand and the air source heat pumps are not used. Thus, when waste heat availability is less than 100% of peak demand, the air source heat pumps will be used only during cold periods when their performance is lower. Consequently, if the air source heat pumps are used for the entire heating season, the central plant average seasonal performance factor will be higher than if their use is limited to cold spells.

Annual cooling performance by the competing systems is shown in Figures 5-5 and 5-6. Since the HP-ICES being studied cannot utilize waste heat during the cooling season, the performance of the three HP-ICES variations is the same in the cooling mode. There is no difference in performance between the HP-ICES and conventional system in the cooling mode. While the resource energy consumed is the same for both systems, HP-ICES does consume more fuel oil while using less electricity.

Peak heating performance by the HP-ICES and conventional systems is shown in Figures 5-7 through 5-10. The conclusions made by comparing the annual performance of the various systems also apply to the peak heating performance. In addition, the HP-ICES use proportionately less resource energy under peak heating conditions, as compared to the annual performance, than the conventional system. Thus, when peak heating conditions occur the HP-ICES will put less of a demand on the mechanisms for energy delivery and help to alleviate short term energy supply problems caused by delivery bottlenecks.

Comparing the central plant performance factors in Figures 5-8 and 5-10 with those in Figures 5-2 and 5-3, it can be seen that the central plant performance is better during the peak period than for the entire heating season. This is due to two factors. First, the main circulating pump runs continuously with an efficiency less than 100% and, as ambient temperatures increase and less dependence is placed on the air source heat pumps, the oil used by the main circulating pump diesel

Figure 5-5. Normalized Energy Balance Diagram
Conventional System Annual Performance - Cooling Mode

Figure 5-6. Normalized Energy Balance Diagram
 HP-ICES Annual Performance - Cooling Mode
 0%, 50%, and 100% Waste Heat

Figure 5-7. Normalized Energy Balance Diagram
Conventional System Performance - Peak Heating Mode

Figure 5-8. Normalized Energy Balance Diagram
 HP-ICES Performance - Peak Heating Mode
 0% Waste Heat

Figure 5-9. Normalized Energy Balance Diagram
HP-ICES Performance - Peak Heating Mode
50% Waste Heat

Figure 5-10. Normalized Energy Balance Diagram
HP-ICES Performance - Peak Heating Mode
100% Waste Heat

represents a greater fraction of the total oil usage, and the average plant performance is reduced. Secondly, the COP of the central plant heat pump centrifugal compressors does not increase very rapidly with increasing ambient temperatures. As the evaporator temperature increases above 10°F, for the compressor studied, a minimum compressor speed must be maintained to prevent surging, resulting in reduced performance during milder temperatures. During a detailed HP-ICES design the compressor selection could be optimized to minimize or avoid this penalty.

Peak cooling mode performance by HP-ICES and the conventional system is shown in Figures 5-11 and 5-12. Whereas annual cooling performance by these systems was identical, during the peak cooling period HP-ICES will help to alleviate energy supply problems as it will at the heating peak. The HP-ICES uses less electricity but requires more oil than the conventional system to provide space peak cooling.

Simultaneous heating and cooling load performance is shown in Figure 5-13 (5-13A and 5-13B) and Figure 5-14. These diagrams were developed assuming equal heating and cooling loads were being met by the HP-ICES and conventional system. The loads appear different in Figures 5-13 and 5-14 because they are normalized with respect to the resource energy required by the respective systems. It can be seen that HP-ICES has a significant performance advantage over the conventional system.

The oil being used by the central plant as shown in Figure 5-14 is fuel for the main circulating pump diesel. Also, no waste heat is being utilized because the heat rejected to the HP-ICES loop by user heat pumps in the cooling mode is sufficient to supply the heat required by user heat pumps in the heating mode. Under these conditions, the performance of HP-ICES is most advantageous as compared to the conventional system.

Figure 5-11.

Normalized Energy Balance Diagram
Conventional System Performance - Peak Cooling Mode

Figure 5-12. Normalized Energy Balance Diagram
 HP-ICES Performance - Peak Cooling Mode
 0%, 50%, and 100% Waste Heat

Figure 5-13A.

Normalized Energy Balance Diagram
 Conventional System Performance - Simultaneous
 Heating and Cooling (Heating Shown Above - Cooling
 Shown in Figure 5-13B)

Figure 5-13B.

Normalized Energy Balance Diagram
 Conventional System Performance - Simultaneous Heating
 and Cooling (Cooling Shown Above - Heating Shown in
 Figure 5-13A)

Figure 5-14.

Normalized Energy Balance Diagram
HP-ICES Performance - Simultaneous Heating and Cooling

5.3 SECOND LAW ANALYSIS

A second law analysis was performed for the HP-ICES and conventional systems by applying the concept of availability to the energy balance diagrams discussed in Section 5.2. Availability is a term used to describe the maximum reversible work that can be obtained from an energy source by bringing that source into equilibrium with its surroundings by means of a reversible process.

Availability can be thought of as the shaft work obtained from a Carnot heat engine operating between the temperature of the energy source and the temperature of the surroundings.

$$\text{Availability} = \text{Carnot work} = E \left(1 - \frac{T_o}{T} \right) \quad (5-1)$$

where (E) is the rate at which energy is extracted from the energy source, (T_o) is the temperature of the surroundings, (T) is the temperature of the energy source, and the quantity in parentheses is the expression for the efficiency of a Carnot heat engine. It can be seen from equation (5-1) that, as the temperature of the source increases with respect to the temperature of the surroundings, the availability will approach the value of (E) and the energy source can be considered as being of high quality or of being a high grade energy source.

In the HP-ICES and the conventional systems, there are three types of energy flows: resource energy, electricity, and thermal energy. Prior to their use, resource energy and electricity are high grade forms of energy, since processes can be conceived by which they could be converted to very high temperature energy sources and used to produce a quantity of shaft work, by means of a Carnot heat engine, essentially equal to the energy values of the sources. Therefore, for the purposes of this analysis, the availability of resource energy and electricity were assumed to be equal to their energy value.

Whenever thermal energy flows, the availability is significantly different from the energy value. The basic equation for defining the availability of an energy flow in a steady flow process, neglecting effects of changes in potential or kinetic energy, is shown below:

$$\text{Availability} = (H - H_o) - T_o (S - S_o) \quad (5-2)$$

where (H) and (S) are the enthalpy and entropy of the energy flow, (T_o) is the temperature of the surroundings, and (S_o) and (H_o) are the entropy and enthalpy of the flow stream in equilibrium with the surroundings.

For thermal energy flows for which the heat transfer medium can be considered as having a constant specific heat, the equation for availability can be written as:

$$\text{Availability} = m' C_p [(T - T_o) - T_o \ln \left(\frac{T}{T_o} \right)] \quad (5-3)$$

where the temperatures are the same as before, (m') is the mass flow rate and (C_p) is the specific heat. Since the transfer of thermal energy in the HP-ICES or conventional system is ultimately by moderate temperature air or water, Eq. (5-3) applies to this analysis.

Although the thermal energy flows shown in Figures 5-1 through 5-14 are shown as single lines, a second or return line is implied for each flow. For example, a residential heat pump draws air from the conditioned space at room temperature, heats it to some higher temperature, and returns it to the conditioned space. Both the supply and return flows have an availability with respect to the surroundings, so the availability transfer rate is equal to the change in availability between the two flow streams. The availability transferred (ΔA) can be represented for this type of process as follows:

$$\Delta A = m' C_p (T_S - T_R) - m' C_p T_o \ln \frac{T_S}{T_R} \quad (5-4)$$

where T_S and T_R represent the temperatures of the supply and return streams. Equation (5-4) can then be rearranged as follows:

$$\Delta A = m' C_p (T_S - T_R) \left[1 - \frac{T_o}{(T_S - T_R)} \ln \frac{T_S}{T_R} \right] \quad (5-5)$$

Noticing that the quantity

$$\frac{m \cdot C_p (T_S - T_R)}{\text{Resource Energy Consumption}}$$

would give the normalized energy values in Figures 5-1 through 5-14, and assuming resource energy and availability are equivalent, the normalized availability transfer for any HP-ICES or conventional system flow stream can be determined by calculating the quantity in brackets in Eq. (5-4) and multiplying by the appropriate normalized energy value. This is the method that was applied in this analysis.

In calculating the availability associated with various thermal energy flows, it was necessary to assume values of the supply and return temperatures and identify the transfer medium being used. For the conventional system, the space heating boilers were assumed to supply hot water at 160°F and the return temperature to be 130°F. Residential heat pumps (heating mode) and electric resistance heaters were assumed to heat room air from 70°F to 100°F and 140°F, respectively. For HP-ICES during the heating season, user heat pumps were assumed to heat room air from 70°F to 100°F, the loop supply and return temperatures to be 60°F and 50°F, respectively, and waste heat to be supplied in the form of water at 80°F with a 70°F return temperature. All air conditioning systems were assumed to cool room air from 78°F to 60°F. The cooling season HP-ICES loop supply and return temperatures were chosen to be 95°F and 105°F, respectively. The temperatures chosen are somewhat arbitrary, but are within the ranges that might be expected for these types of thermal energy transfer processes.

The results of the second law analysis are shown in Figures 5-15 through 5-28. The value of the temperature of the surroundings (T_o) and the conditioned space temperature (T_s) are shown next to the block labelled conditioned space. Normalized availabilities are identified by an (A). The availability efficiency (availability output divided by availability input) is indicated by (ψ). Note that for air conditioning

systems ψ is calculated as the availability input from the conditioned space divided by the availability of the electric energy input. The loss of availability associated with various devices and processes is indicated by an (I). Although power plant reject heat, boiler stack losses, and energy rejected to ambient by air conditioning systems and cooling towers has an availability with respect to the surroundings, availabilities have not been assigned because with respect to the HP-ICES and conventional system these energy flows represent lost availability.

The conclusions reached after inspecting Figures 5-15 through 5-28 are essentially the same as those reached from inspecting the energy balance diagrams (Figures 5-1 through 5-14). In the heating mode of operation, both annual (Figures 5-15 through 5-18) and peak (Figures 5-21 through 5-24) HP-ICES transfers more availability per unit resource availability consumed than the conventional system. HP-ICES is proportionally better than the conventional system during peak heating conditions than for the heating season as a whole. The use of waste heat improves the performance advantage of HP-ICES.

Annual cooling performance (Figures 5-19 and 5-20) is essentially identical for HP-ICES and the conventional alternative; however, HP-ICES has a decided performance advantage in the peak cooling mode (Figures 5-25 and 5-26). When simultaneous heating and cooling occurs as shown in Figures 5-27 (A and B) and 5-28, HP-ICES outperforms the conventional system in both modes of operation. It can be seen that the availability efficiency (ψ) of the conventional space conditioning equipment is lower than that of the HP-ICES user equipment. Also, the availability efficiencies are significantly less than energy efficiencies and performance factors.

5.4 THERMAL ANALYSIS SUMMARY

The first and second law analyses discussed in Sections 5.2 and 5.3 have shown the thermal performance advantages of HP-ICES with respect to the conventional system in several modes of operation. In this section, these advantages are emphasized again. In Table 5-2, the ratio

Figure 5-15.

Normalized Availability Diagram
Conventional System Annual Performance - Heating Mode

Figure 5-16.

Normalized Availability Diagram
 HP-ICES Annual Performance - Heating Mode
 0% Waste Heat

Figure 5-17. Normalized Availability Diagram
HP-ICES Annual Performance - Heating Mode
50% Waste Heat

Figure 5-18. Normalized Availability Diagram
HP-ICES Annual Performance - Heating Mode
100% Waste Heat

Figure 5-19.

Normalized Availability Diagram
 Conventional System Annual Performance - Cooling Mode

Figure 5-20.

Normalized Availability Diagram
 HP-ICES Annual Performance - Cooling Mode
 0%, 50%, and 100% Waste Heat

Figure 5-21.

Normalized Availability Diagram
Conventional System Performance - Peak Heating Mode

Figure 5-22. Normalized Availability Diagram
HP-ICES Performance Peak Heating Mode
0% Waste Heat

Figure 5-23. Normalized Availability Diagram
HP-ICES Performance - Peak Heating Mode
50% Waste Heat

Figure 5-24. Normalized Availability Diagram
HP-ICES Performance - Peak Heating Mode
100% Waste Heat

Figure 5-25.

Normalized Availability Diagram
Conventional System Performance - Peak Cooling Mode

Figure 5-26: Normalized Availability Diagram
HP-ICES Performance - Peak Cooling Mode
0%, 50%, and 100% Waste Heat

Figure 5-27A.

Normalized Availability Diagram
 Conventional System Performance - Simultaneous
 Heating and Cooling (Heating Shown Above -- Cooling
 Shown in Figure 5-27B)

Figure 5-27B Normalized Availability Diagram
 Conventional System Performance - Simultaneous
 Heating and Cooling (Cooling Shown Above - Heating
 Shown in Figure 5-27A)

Figure 5-28

Normalized Availability Diagram
 HP-ICES Performance - Simultaneous Heating and Cooling

of HP-ICES to conventional system purchased energy requirements and resource energy requirements are shown. All HP-ICES use significantly less resource energy than the conventional system. The HP-ICES also use less electricity and, for the 50% and 100% waste heat utilization cases, use less oil. Similar information is presented in Table 5-3 for peak heating mode operation. Comparing the data in Tables 5-2 and 5-3 it is apparent that the performance advantage of HP-ICES as compared to the conventional system during the peak heating period is even more significant than for the heating season as a whole.

During the cooling season, HP-ICES uses 7.5×10^9 Btu of oil whereas the conventional system has no oil requirements. During the peak cooling period HP-ICES oil consumption is 2.7×10^6 Btuh. However, the HP-ICES electricity usage for the cooling season and the peak cooling period is 85% and 79%, respectively, of the conventional system usage. Resource energy consumption by HP-ICES during the cooling season and peak period is equal to 100% and 81%, respectively, of the conventional system values. Thus, HP-ICES, while it does reduce the negative effects of the conventional system peak cooling energy usage, does consume more oil during the cooling season.

An annual comparison for HP-ICES and the conventional alternative is shown in Table 5-4 where it can be seen that on an annual basis HP-ICES will use significantly less electricity and resource energy. However, even with 100% waste heat utilization, HP-ICES will use more oil. Note that this would not have been true if oil fired boilers compared to electric resistance heaters had been selected as the conventional system for apartment buildings.

For comparison, the energy usage by the conventional system for various modes of operation (peak and annual) is presented in Table 5-5.

Table 5-2. Ratio of HP-ICES To Conventional
System Energy Use - Heating Season

HP-ICES Percent Waste Heat Utilization	Ratio of HP-ICES to Conventional System Purchased Energy Requirements - Heating Season		Ratio of HP-ICES to Conventional System Resource Energy Requirements - Heating Season
	<u>Oil</u>	<u>Electricity</u>	
0	1.77	0.59	0.74
50	0.89	0.56	0.61
100	0.83	0.56	0.60

Table 5-3. Ratio of HP-ICES to Conventional System
Energy Use - Peak Heating Mode

HP-ICES Percent Waste Heat Utilization	Ratio of HP-ICES to Conventional System Purchased Energy Requirements - Peak Heating Mode		Ratio of HP-ICES to Conventional System Resource Energy Requirements - Peak Heating Mode
	<u>Oil</u>	<u>Electricity</u>	
0	1.46	0.44	0.57
50	0.53	0.43	0.48
100	0.31	0.43	0.41

Table 5-4. Ratio of HP-ICES to Conventional
System Energy Use - Annual Summary

<u>HP-ICES Percent Waste Heat Utilization</u>	<u>Ratio of HP-ICES to Conventional System Annual Purchased Energy Requirements</u>		<u>Ratio of HP-ICES to Conventional System Annual Resource Energy Requirements</u>
	<u>Oil</u>	<u>Electricity</u>	
0	2.02	0.63	0.78
50	1.08	0.61	0.67
100	1.02	0.61	0.66

Table 5-5. Conventional System Energy Use

Period of Energy Consumption	Conventional System Purchased Energy Requirements		Conventional System Resource Energy Requirements
	Oil	Electricity	
Heating Season	39.2×10^9 Btu	88.9×10^9 Btu	306.1×10^9 Btu
Peak Heating Period	24.3×10^6 Btuh	59.1×10^6 Btuh	201.6×10^6 Btuh
Cooling Season	--	16.7×10^9 Btu	50.1×10^6 Btuh
Peak Cooling Period	--	32.6×10^6 Btuh	97.8×10^6 Btuh
Annual	39.2×10^9 Btu	105.6×10^9 Btu	356.2×10^9 Btu

6. HEAT PUMP-ICES ECONOMICS

6.1 INTRODUCTION

The economic feasibility of HP-ICES was tested by comparing the life cycle cost of HP-ICES over the 20-year period 1980 to 2000 with the life cycle cost of the conventional system. The HP-ICES life cycle cost was calculated as the sum of the life cycle costs of the central HP-ICES plant and loop piping and the life cycle costs of the HP-ICES customer owned space conditioning equipment. The conventional system life cycle cost was calculated as the sum of the life cycle costs associated with the various types of space conditioning equipment assumed to be used by the reference community without HP-ICES.

In addition to determining the life cycle costs for the HP-ICES and conventional systems for the reference community, the sensitivity of HP-ICES economics to several factors was investigated. These factors include the type of HP-ICES ownership (i.e., privately owned utility, community cooperative, or municipally owned utility), community size, community energy density (i.e., peak heating demand per acre), energy cost escalation rate, number of shifts per day worked by HP-ICES central plant maintenance personnel, and cost of loop piping.

The body of this section of the report discusses HP-ICES economic feasibility. Some of the analyses used are described here, and more detailed descriptions are given in Section 11.

6.2 HP-ICES AND CONVENTIONAL SYSTEM USER ECONOMIC ANALYSIS

As stated in the introduction, HP-ICES economic feasibility was examined for the years 1980 to 2000. Annual costs were calculated for the various building types in the reference community for both HP-ICES space conditioning systems (i.e., HP-ICES user owned equipment). The

methods used to calculate annual costs for residential users, commercial/ industrial users, and not-for-profit users (i.e., schools, churches and recreation centers) in year (i) are shown below:

$$\text{Annual Cost (Residential Users)} = \text{Loan Payment} + \text{O\&M}(i) + \text{Energy Costs}(i) + \text{Property Taxes}(i) - [(\text{Interest on Loan}(i) + \text{Property Taxes}(i)) \times \text{Federal Personal Income Tax Rate}]$$

$$\text{Annual Cost (Commercial/Industrial Users)} = [\text{Loan Payment} + \text{O\&M}(i) + \text{Energy Costs}(i) + \text{Property Taxes}(i)] \times (1 - \text{Federal Corporate Income Tax Rate})$$

$$\text{Annual Cost (Schools, Churches, Recreation Centers)} = \text{Loan Payment} + \text{O\&M}(i) + \text{Energy Costs}(i)$$

Operation and maintenance costs (O&M costs), and property taxes were escalated at a rate of 5% per year. The electricity and fuel oil escalation rates employed were 6.5% and 7% respectively for the base case. Other energy escalation rates were examined as part of the sensitivity analysis.

The method used to calculate annual costs for commercial and industrial users is an approximation, in that it assumes that the loan is amortized at the same rate as the equipment is depreciated. In any given year, this method will give an annual cost different from the true value but, over the life of the system, this method and a more rigorous one will give essentially the same results.

The life cycle costs for the conventional system and HP-ICES users are shown in Table 6-1. It can be seen in Table 6-1 that each HP-ICES user has a lower life cycle cost as compared to an equivalent conventional system user. However, the HP-ICES user life cycle costs shown in Table 6-1 do not include the cost of energy extracted from the HP-ICES loop or any credit for rejecting heat to the loop during the heating season. This cost/credit is accounted for in the HP-ICES central plant and piping loop analysis of the following section.

Table 6-1. User Life Cycle Costs for Reference Community HP-ICES and Conventional Systems (Does not include HP-ICES central plant costs)

User	HP-ICES (\$x10 ⁶)	Conventional System (\$x10 ⁶)
Residential	26.3	36.9
Commercial/Industrial	10.6	18.5
Schools, Churches, Recreation Centers	1.3	3.5
Totals	38.2	58.9

6.3 HP-ICES CENTRAL PLANT ECONOMIC ANALYSIS

The HP-ICES central plant includes all HP-ICES equipment located outside of user buildings. This includes the central facility, loop piping, Btu meters and waste heat heat exchangers. The development of the HP-ICES central plant installed costs and the economic analysis employed is discussed in Section 11.

The installed costs for the HP-ICES central plant in the reference community are shown in Table 6-2. It can be seen that the loop piping is the single largest cost item (ranging from 59% to 71% of the total cost). As the percent waste heat utilization increases, the cost of the central plant building and equipment decreases rapidly. However, this is offset somewhat by the added cost of the waste heat heat exchangers.

The life cycle costs for the three cases shown in Table 6-2 are given in Table 6-3. These life cycle costs were calculated assuming the central plant was owned and operated by a privately owned utility. As shown in Table 6-3, the use of waste heat has a significant beneficial

Table 6-2. HP-ICES Central Plant Installed Costs

Component	Installed Cost in 1980 (\$x10 ⁶) Percent Waste Heat Utilization		
	0%	50%	100%
Building	0.845	0.720	0.565
Central Plant Equipment	3.401	2.980	1.084
Loop Piping	8.416	8.416	8.416
Btu Meters	1.500	1.500	1.500
Waste Heat Heat Exchangers	0	0.141	0.283
Totals	14.162	13.757	11.848

Table 6-3. HP-ICES Central Plant Life Cycle Cost

Percent Waste Heat Utilization	Life Cycle Cost (\$x10 ⁶)
0%	34.3
50%	30.2
100%	25.9

effect on HP-ICES economics. The life cycle cost for the 100% waste heat case is 14% less than for the 0% waste heat case.

6.4 ECONOMIC COMPARISON: HP-ICES VS. CONVENTIONAL SYSTEM

The life cycle cost for HP-ICES equals the life cycle cost to the users (Table 6-1) plus the life cycle cost of the central plant (Table 6-3). For comparison, the life cycle costs for HP-ICES and the conventional system are shown in Table 6-4. It can be seen that HP-ICES is more expensive than the conventional system. Actually, HP-ICES is 1.09

Table 6-4. HP-ICES and Conventional System Life Cycle Costs

System	Life Cycle Cost (\$x10 ⁶)
HP-ICES - 0% Waste Heat	72.4*
HP-ICES - 50% Waste Heat	68.3*
HP-ICES - 100% Waste Heat	64.0*
Conventional System	58.9

*Privately Owned Utility

to 1.23 times as expensive as the conventional system. Thus, while HP-ICES in the reference community would significantly reduce resource energy consumption, it would not be an especially cost competitive option relative to the conventional system.

6.5 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to determine the effect of using different criteria on the economic viability of the HP-ICES. This sensitivity analysis was to determine how the results are affected by changes in such factors as type of ownership, community size, community energy density, energy cost escalation rates, etc.

6.5.1 Type of Ownership

The initial economic analysis for HP-ICES assumed the central plant and loop piping were owned by a privately owned utility (base case). As alternatives, the central plant could be owned either by a cooperative or by a municipal utility. The differences between the three types of ownership are the desired profits and the type of financing. The privately owned public utility was assumed to be allowed a 9% return on investment, whereas in the cooperative and the municipally owned HP-ICES the revenues from operation equal the annual cost associated with owning and operating the central plant. The privately owned utility

was assumed to be 50% debt financed (11% interest) and 50% financed by a stock offering. The cooperative and municipal systems were assumed to be 100% debt financed with the cooperative paying 11% interest and the municipality 6.5% interest.

The effect of type of ownership on HP-ICES economics is shown in Figure 6-1. The ratio of the life cycle cost for HP-ICES to that for the conventional system is shown as a function of type of ownership and waste heat utilization. Since the conventional system does not utilize waste heat, it is represented as a straight line in Figure 6-1. It can be seen that municipal ownership is the most cost effective, however, it is only competitive with the conventional system with 100% waste heat utilization.

6.5.2 Community Size

The base case economic analysis of HP-ICES was for a reference community of a specific size.* Here, the effect of community size on HP-ICES economic feasibility is examined. The life cycle cost for HP-ICES was determined for communities half and twice the size of the reference community having the same composition as the reference community. As the size of the community varies, so does the length and size of the piping, the size of the central plant, and energy consumption by the central plant and the users. The method used to determine the variation of these factors with community size and their effect on HP-ICES initial cost are discussed in Section 11. The results of this analysis are shown in Figure 6-2 where the ratio of the life cycle cost of HP-ICES is shown as a function of community size and percent waste heat utilization. It can be seen that, for the community size range considered, the ratio of HP-ICES life cycle cost to that of the conventional system is essentially a constant, and therefore, HP-ICES economics are not very sensitive to community size.

*10,000 population, see Section 11.1

Figure 6-1 Effect of Type of Ownership on HP-ICES Economics

Figure 6-2. HP-ICES and Conventional System Life Cycle Cost Comparison as a Function of Community Size

6.5.3 Community Energy Density

The energy density of the reference community based on peak heating demand is 0.119×10^6 Btuh/acre. By comparison, the central core of a large city can have an energy density as high as 0.97×10^6 Btuh/acre (Reference 6-1.) The effect of several levels of energy density on HP-ICES economics was investigated. The results are shown in Figure 6-3 where the uppermost line represents base case HP-ICES cost. The lower lines show the advantage of service areas with higher energy densities.

It can be seen in Figure 6-3 that, at a community energy density of approximately 0.45^* , HP-ICES with 100% waste heat utilization will just be competitive with the conventional system. As the community energy density increases, HP-ICES is competitive with the conventional system at lower values of waste heat utilization. Specifically, for community energy densities of 0.537^* and 0.805^* , the minimum waste utilization required for HP-ICES to be competitive are 90% and 70%, respectively. By extrapolation, it appears that HP-ICES serving a dense urban area (energy density = 0.97^*) would only require 45% waste heat utilization to be competitive with the conventional system.

6.5.4 Energy Cost Escalation

The economic analyses described previously have used escalation rates of 6.5% and 7% for electricity and oil, respectively. The effect of higher escalation rates on HP-ICES economics is shown in Figure 6-4. The uppermost line in Figure 6-4 shows base case economic performance. The lower two lines show the advantage to HP-ICES of higher energy cost escalation rates. However, only at the highest set of escalation rates does HP-ICES become economically competitive with the conventional system, if no waste heat is utilized.

*units are 10^6 Btuh/acre

Figure 6-3. Effect of Community Energy Density on HP-ICES Economics

Figure 6-4. Effect of Annual Energy Cost Escalation Rate on HP-ICES Economics

6.5.5 Central Plant Maintenance Personnel

The previous analyses are based on the assumption that at least one maintenance engineer will always be on duty at the central plant. This would require a maintenance staff consisting of a chief engineer, four watch engineers and a clerk with a total annual salary in 1980 of \$126,000 including 28% fringe benefits. If the central plant is highly automated, it would be possible to reduce labor costs by employing only a chief engineer and a clerk for one shift per day, five days a week. In this case, the total annual salary would be \$44,800. The effect of this reduced labor cost is to reduce the HP-ICES life cycle cost by only 2.5%, indicating that the cost of labor does not have a significant effect on the economic competitiveness of HP-ICES.

6.5.6 Loop Piping Costs

As indicated previously, the loop piping represents a significant fraction of the total HP-ICES central plant installed cost. Therefore, an analysis was performed to determine the advantages that could be gained if piping costs were reduced. It was determined that, even if the piping installed cost was zero, HP-ICES without waste heat utilization would not be competitive. For HP-ICES with 50% and 100% waste heat reduction, piping installed costs would have to be reduced by 86% and 46%, respectively, before these systems become economically viable.

The possibility of reducing the piping installed cost (see Table 6-2) by even 46% is doubtful. Based on cost data in the 1978 Dodge Manual for Building Construction Pricing and Scheduling, the installed cost of plastic pipe is not significantly less than that for the schedule 40 steel pipe on which the costs in Table 6-2 are based. Therefore, it is unlikely that HP-ICES would be economically viable in a community similar in nature (i.e. low energy density) to the reference community. This conclusion applies to private utility and cooperative ownership of HP-ICES as shown in Figure 6-1. A municipally owned HP-ICES would be economically attractive when the waste heat utilization is near 100%.

6.6 SUMMARY

As a result of the sensitivity analyses, it can be concluded that HP-ICES can be a viable, economically competitive alternative to present conventional energy systems. Optimum conditions are

- municipal ownership
- waste heat utilization
- high energy density.

The economics of HP-ICES are insensitive to community size for communities one-half to twice the size of the reference community. HP-ICES becomes more attractive as the energy density (peak heating demand/acre) of the service area increases and as energy cost escalation rates increase.

The sensitivity analyses presented in this section were used to obtain the breakeven points between HP-ICES and conventional systems; see Section 4.2.1.

7. ENVIRONMENTAL IMPACTS

7.1 INTRODUCTION

Energy systems of the scope and size of HP-ICES will affect the environment. The expected environmental impacts from the installation and operation of HP-ICES are discussed in this section of the report. The HP-ICES environmental impacts have been categorized as follows:

HP-ICES Environmental Impact Categories

- Operating energy use
- Noise pollution
- Thermal pollution
- Impact on air quality
- Effect on environment during construction
- Resources consumed during construction
- Consequences of equipment failure
- Land utilization
- Consequences of Maintenance
- HP-ICES System

These HP-ICES environmental impact categories are discussed separately and the impacts associated with HP-ICES are compared to those for the conventional system.

7.2 OPERATING ENERGY USE

The HP-ICES and conventional system purchased and resource energy requirements are dealt with in detail in Section 5. Briefly, the HP-ICES uses significantly less resource and purchased energy than the conventional system. HP-ICES with no waste heat utilization uses less resource energy and total purchased energy, but uses more oil than the

conventional system. Since oil is a relatively scarce resource and can be used more beneficially for other purposes than space conditioning, an increase in oil usage as compared to the conventional system is a significant adverse environmental impact. However, as shown in Section 5, if HP-ICES utilizes waste heat to a significant extent during the heating season, oil consumption will be less than it would for the conventional system.

The total energy requirements by HP-ICES at both the heating and cooling peaks are lower than for the conventional system. Thus, HP-ICES will help to alleviate short term energy supply problems caused by overloading of the energy delivery mechanisms during periods of peak demand. By using less energy, HP-ICES will also reduce the negative environmental impacts associated with the energy delivery mechanisms.

7.3 NOISE POLLUTION

The noise level within the various buildings in an HP-ICES community will remain essentially the same as it would have been with the conventional system since the number of pumps, fans, etc. will be similar. However, the HP-ICES central plant could be a significant source of noise. This plant may have one or more of the following: a diesel engine driving the HP-ICES loop circulating pump, diesel engine driven air-to-water heat pumps, heat pump evaporator fans, cooling tower fans and a variety of pumps and motors. The diesels will be muffled, but the noise would still be objectionable in a residential neighborhood. The fans alone will create an objectionable noise level in the quieter sections of the community. It is expected that every attempt will be made to keep the noise level at the HP-ICES central plant as low as possible, but this will not completely solve the problem. Thus, it is expected that the central plant will be located in an area zoned for light manufacturing where the noise level from the central plant will be similar to that of the surrounding industry.

7.4 THERMAL POLLUTION

Conventional system thermal pollution in the community will result from boiler stack losses and heat rejection by air conditioning systems. HP-ICES thermal pollution in the community will be due to unrecovered heat from the diesel engines in the central plant and heat rejection from the HP-ICES loop to ambient during the cooling season. During the winter, HP-ICES will reject slightly less heat to the community environment than the conventional system. During the summer, HP-ICES will reject 8% more heat to the community environment. The heat rejection by the conventional system is distributed throughout the community whereas heat rejection by HP-ICES takes place at the central plant. Although a single heat rejection point could cause a greater environmental impact than distributed sources, locating the HP-ICES central plant away from residential and commercial areas should help alleviate the problem.

The conventional and HP-ICES systems will also cause thermal pollution outside the community due to their dependence on electric energy. Approximately 2/3 of the resource energy used to generate electricity at an electric generating station is lost or rejected to the environment. HP-ICES uses significantly less electricity than the conventional system. Consequently, HP-ICES will have an overall beneficial effect on thermal pollution.

7.5 IMPACT ON AIR QUALITY

Both the conventional system and HP-ICES use purchased energy in the form of oil and electricity. The oil is consumed on-site and the electricity is generated outside of the reference community. The emissions from oil using equipment will directly affect the reference community's air quality. Emissions from the electric generating station, while not released in the community, will affect the air quality in the region in which the community is located. The HP-ICES, which does not use waste heat annually, uses approximately twice as much oil and half as much electricity as does the conventional system. Thus, this HP-ICES

will have a much greater impact on local air quality but may be no worse than the conventional system if overall regional air quality is considered. The HP-ICES which utilize waste heat require less electricity and oil per year than the conventional system and will have a positive impact on air quality both locally and regionally.

7.6 EFFECT ON ENVIRONMENT DURING CONSTRUCTION

The major impacts on the environment which occur during construction of HP-ICES will be due to the installation of the buried piping loop and construction of the central plant.

The HP-ICES being studied is not considered to be viable for highly developed areas because of the difficulty in finding room beneath the streets for the loop piping because this area is already crowded with utility conduits, pipes and cables, and the high cost of burying pipes under paved streets. However, it is unlikely that the HP-ICES will be completed much before the first user is ready to come on-line and, as the community grows, the HP-ICES will be expanded.

The potential environmental impacts resulting from construction of HP-ICES include the generation of dust during the trenching and back-filling required for the loop piping and grading of the central plant site, disruption of traffic patterns, and emissions and noise from construction equipment. These impacts will not be permanent, but only last for the period of construction. Assuming the HP-ICES location is not well developed, these impacts can be minimized by careful planning.

7.7 RESOURCES CONSUMED DURING CONSTRUCTION

The major resources consumed during construction of HP-ICES include the steel in the piping and equipment, cement, fuel used by the construction equipment, and labor. The resources used to make the construction materials, including energy, should also be charged to HP-ICES. An energy payback period was not derived for HP-ICES but it appears to be relatively short since HP-ICES uses significantly less resource energy

than the conventional system. A positive benefit from HP-ICES will be the creation of jobs. More labor will be required for the construction of HP-ICES than for the conventional system.

7.8 CONSEQUENCES OF EQUIPMENT FAILURE

The buildings connected to an HP-ICES will depend on it for their space conditioning requirements. If the HP-ICES experiences a major failure these services could be interrupted. During the cooling season, an HP-ICES failure could cause commercial and industrial establishments to close and lose revenue. An HP-ICES failure in the winter could cause water line freezing and building structural damage.

The failure of HP-ICES to provide the services for which it was designed could be caused by a fire, failure of a loop circulating pump, electrical outage, break in the loop piping, etc. A break in the loop piping, besides interrupting HP-ICES services, could also cause pavement and property damage.

The potential for interruption of HP-ICES services cannot be eliminated but can be minimized by insuring that the system is installed properly and receives adequate preventive maintenance.

7.9 LAND UTILIZATION

The land required by HP-ICES in excess of that required by the conventional system will consist of the central plant site and the underground volume occupied by the loop piping. The area required for the central plant is relatively small compared to the total community area. For the reference community, the area of the central plant site is approximately 0.2% of the gross area of the community. The underground volume occupied by the loop piping is important because, as the community develops, more utilities will compete for the space beneath the streets. This is a difficult situation to avoid. The only apparent solution is to plan for this eventuality and develop good lines of communication between the competitors for this space.

7.10 CONSEQUENCES OF MAINTENANCE

Maintenance of HP-ICES would involve maintenance of the HP-ICES user owned equipment, loop piping, and central plant equipment. The major environmental impact from poor maintenance of user owned equipment would be the loss of refrigerant. The refrigerants presently in use in air conditioning and heat pump systems are nontoxic, but their migration into the upper atmosphere has been cited as a danger to the earth's ozone layer. Therefore, abnormal releases of refrigerant are to be avoided; however, the total cooling tonnage of user owned equipment in an HP-ICES community is the same as for a non HP-ICES community. Consequently, the maintenance of user owned HP-ICES equipment will not have any more impact on the environment than would be the case for the conventional system.

Maintenance of the HP-ICES loop piping will only be required if there is a pipe break. The occurrence of a break itself may have unfortunate consequences as discussed previously. Repairing the break will cause a relatively minor disturbance to the environment. The major effect will be a disruption of traffic. This will be a short term condition since a pipe break is a serious problem in an HP-ICES system and must be repaired quickly.

Maintenance of HP-ICES central plant equipment will have a minor impact on the environment. The refrigerant inventory in the central plant is low compared to the community as a whole. Maintenance of central plant equipment may create noise, but locating the plant in a non-residential area will alleviate this problem.

7.11 DISPOSAL OF THE HP-ICES SYSTEM

When the HP-ICES system is retired, the central plant will have to be demolished, but the loop piping and user owned equipment will most likely remain in place. Demolishment of the central plant will create noise, dust and cause traffic problems for a short period of time. Once the plant is removed, however, the land can easily be returned to its original condition.

8. HP-ICES EXPANSION

A basic objective of the HP-ICES development program is to conserve energy; however, it is assumed that, if HP-ICES is implemented, it will be because it is economically competitive with alternative systems. Therefore potential users will want to be connected to the system. If HP-ICES cannot expand rapidly enough to take on new customers, these customers may have to install conventional systems. This would diminish the economic advantage of HP-ICES because the service area energy demand density as perceived by HP-ICES would be less than if all buildings within the service area were HP-ICES customers. As shown in Section 6, the HP-ICES economics benefit from increased service area demand densities. Further, the impact of HP-ICES on community energy consumption would be reduced. Thus, it is important that HP-ICES not lose potential customers.

If HP-ICES is to maximize its effect on the community, it must be able to expand in unison with the community it serves. Since community growth rates are rarely constant and development plans are not always adhered to, the HP-ICES must be adaptable to relatively sudden increases in load.

The problem of expanding to meet the load will be particularly important during system startup since supplying new customers can only be accomplished by laying pipe mains. Once the system has developed, providing service to new customers can be accomplished in several ways as will be discussed later.

The initial growth of HP-ICES must be carefully planned to maximize HP-ICES effectiveness. During the planning stage, potential users must be informed of the HP-ICES benefits and the scheduling of service availability. The users must have sufficient advance notice of the HP-ICES plans so that mismatches between the time when service is available and the time when the user connects to the system are minimized. If the

users' plans are such that he cannot wait for HP-ICES service, he can install a space conditioning system of the type described in Section 3 and use a temporary cooling tower and boiler until he connects to HP-ICES. With sufficient advance notice potential users with existing buildings can evaluate the feasibility of modifying their equipment in time to utilize HP-ICES at the earliest opportunity. With proper planning and scheduling, the growth of HP-ICES in size and capacity can be matched to the growth of the load and the economic impact of this concept maximized.

While the users are preparing to connect to HP-ICES, the HP-ICES central plant and piping must be installed. It is envisioned that the central plant equipment will be modular so the plant capacity can be increased by adding more modules as the connected load increases. It is doubtful that a piping loop such as that shown in Figure 3-1 would ever be used by an actual HP-ICES. During the early growth period, piping costs must be held to a minimum. Rather than constructing a piping loop such as that shown in Figure 3-1, it is more likely that the piping system would have more hairpin loops such as that running from the ICES plant in the lower right of Figure 3-1 through the center of the community. Depending on how the community grows, it may be more practical to run hairpin loops out to each new load center as it develops. The resulting piping arrangement would be less than optimum (i.e., use more pipe) than other arrangements but could be a more cost effective way of increasing HP-ICES capacity. Unless distribution mains are oversized, reaching major new load centers by extending existing mains is not a viable alternative. The flow rate through the existing mains would have to be increased resulting in increased pressure drop and pumping power.

After an HP-ICES passes the initial startup period, expansion can be accomplished by some combination of the following: increasing central plant capacity, adding new central plants to the system, or installation of new distribution mains. Modest requirements for increased system capacity can probably be met in less time and at less expense by increasing central plant capacity or adding a new central plant to the

system. The choice of whether to increase plant capacity or add new distribution piping will depend on the nature of the existing system and the size and location of the new load to be served.

Economically advantageous startup and expansion procedures have been developed in Sweden for district heating systems (Ref. 8-1). They are quoted, in part, below.

"When a municipal authority starts the construction of a district heating network, heat generation equipment must be installed at the same rate as the subscribers are connected to the network. One or several boiler stations are therefore initially installed, and these are usually rated between 3 MBtu/h and 20 MBtu/h. The control equipment is designed so that the station can be operated entirely unmanned, with only some essential attendance during daytime. However, relatively much work is involved, particularly when numerous mobile stations are in operation on the same network.

In addition to the relatively low cost, another major advantage of the mobile station is that it can be easily moved from a district that has been connected to a major network to another district in which construction of the district heating network is in progress. This offers maximum utilization of the stations.

The useful life of a station of this nature is dependent on the operating time and the maintenance it receives, although a figure usually estimated is about five years. But many stations have been in operation appreciably longer than five years."

It is readily apparent that these procedures are equally applicable to the startup and expansion of HP-ICES. While completely prepackaged central HP plants are not presently being manufactured, the modular construction of the plant easily lends itself to the "transportable" concept. Since one or more central plants can be located almost anywhere along the central loop, the proposed method does not exact significant operational penalties. Although only one HP-ICES central plant is shown in Figure 3-1, in some cases it may be more advantageous to have several central plants distributed around the community perimeter. As new load

centers appear, they could be served from the nearest central plant with a minimum of additional piping.

Increasing the capacity of an existing central plant is relatively easy compared to adding new distribution mains. Plant capacity can be increased by adding more equipment modules or by increasing the size of one or more of the existing units. The best method to be employed in a given situation depends on the particular characteristics of the system.

9. HP-ICES VARIATIONS

9.1 INTRODUCTION

An HP-ICES concept has been discussed in detail in previous sections of this report. This section describes variations on the basic concept which could lead to improved performance.

9.2 WASTE HEAT UTILIZATION

The performance of the Heat Pump ICES described in this report will be improved significantly if waste heat is added to the main circulation loop during the heating season. By utilizing available waste heat, the size and number of the air source heat pumps in the central ICES plant can be reduced or even eliminated. The main circulation loop water temperature is required to be no lower than 60°F during the heating season. Its maximum allowable temperature is 95°F. Thus, nearly all waste heat sources can be used by the ICES system, although it will be necessary to degrade the temperature of waste heat sources with temperatures greater than 95°F.

Potential waste heat sources include industrial process cooling water, electric generating station cooling water, and waste heat recovery from on-site electric generation. The quantity of waste heat available will vary from site to site and could range from zero to 100% of the annual heat requirements of the system.

9.2.1 Industrial Waste Heat Utilization

A waste heat source must be reasonably close to an HP-ICES community in order that the cost of recovering and transporting the heat to the community does not exceed the savings resulting from the use of the heat. Consequently, the most likely candidate sources of industrial waste heat

are those industries which may be located near commercial and/or industrial areas. Major industries such as steel mills, paper mills, chemical plants, refineries, etc. are often large enough that a single plant could provide all of the waste heat required by an HP-ICES; they would tend to operate on a three shift per day basis so that the waste heat supply would be fairly constant. Although the cost of connecting HP-ICES to a single waste heat source would be less than for multiple sources, dependence on a single source would mean that HP-ICES was more vulnerable to a total loss of its waste heat supply. Therefore, it may be desirable to have multiple waste heat sources connected to HP-ICES.

There are many moderately sized industries which tend to be located in developed areas which could supply a fraction of the waste heat needs of an HP-ICES. Examples include rubber processing plants, meat processing plants, auto parts rebuilding facilities, pharmaceutical firms and canning factories. Thus, while a single industry of this type may not supply all the waste heat needs of an HP-ICES, several of them together could and would help to assure continuity of waste heat supply.

The recovery of industrial waste heat for use by HP-ICES requires the installation of a heat exchanger between the waste heat source and the HP-ICES system's main circulation loop to prevent contamination of the loop. It has been assumed in this study that the HP-ICES owner would install and maintain the heat exchanger. The cost of several sizes of plate and shell and tube heat exchangers is shown in Table 9-1. It can be seen that for small heat exchangers the shell and tube type is less expensive, however, at heat transfer rates over a million Btuh, the plate heat exchanger costs less. In addition to the heat exchanger cost, utilization of industrial waste heat will require expenditures for connecting the heat exchanger to the HP-ICES loop and industrial process, and possibly for modification of the industrial process equipment. For the economic analyses discussed in Section 6, it was assumed that the total installed cost of the waste heat recovery system was three times the heat exchanger cost. The actual cost for a specific installation could be higher or lower depending on the location of the industry with

respect to the HP-ICES system and the nature of the waste heat source. Although the heat exchanger costs shown in Table 9-1 are for liquid to liquid units, it would also be feasible to recover heat from hot waste gases.

Table 9-1. Heat Exchanger Costs

Design Heat Transfer Rate (Btuh)	Plate Heat Exchanger Cost ¹	Shell and Tube Heat Exchanger Cost ²
50,000	\$ 1500	\$ 336
1x10 ⁶	4000	4850
10x10 ⁶	14000	-
50x10 ⁶	55,000	250,000
100x10 ⁶	110,000	500,000

1. Private communication with Jeffrey Kerner, Alberts & Assoc., Inc., Philadelphia, PA (11-7-78)
2. Private communication with John Lerro, Devicengineering, Media, PA. (11-9-78)

Waste heat is only useful to HP-ICES during the heating season. During the cooling season, when HP-ICES users are rejecting heat to the HP-ICES loop, the loop will be operating at its maximum allowable temperature. The addition of waste heat to the loop at this time would create an additional load on the central plant's heat rejection system. To alleviate this added load, it is envisioned that the waste heat available would not be added to the main circulation loop but would be rejected to ambient at its source. Consequently, the industrial suppliers of waste heat must install and maintain the heat rejection system they would have used had the HP-ICES not been available. However, since the HP-ICES owner will install and maintain the industrial process to

HP-ICES loop heat transfer equipment, the expense to the industrial plant will be minimal. The industrial plant may even save money due to reduced operating and maintenance expenses for its on-site heat rejection equipment.

9.2.2 Electric Generating Station Waste Heat Utilization

Electric utility steam power plant cooling water could also be a source of waste heat for a heat pump ICES system. Typically, the cooling water experiences a 20°F rise as it passes through the condenser. The power plant waste heat could be recovered by direct heat exchange or by means of a water-to-water heat pump. A 100 MW steam power plant (small by today's standards) could easily supply all of the heat required by the ICES system.

Direct heat exchange is technically feasible, but requires that the power plant cooling water exit temperature be sufficiently higher than the ICES system's circulating loop temperature to allow sufficient heat to be transferred without the use of an excessively large heat exchanger. Depending on local climatic conditions and the plant's type of cooling system (once-through from a river or lake, or recirculation through a cooling tower), the exiting cooling water temperature may not be sufficiently higher than the minimum required ICES loop temperature for direct heat exchange during the coldest part of the heating season. This is particularly true for plants with one-through cooling. However, most new plants now have cooling towers and would tend to have a higher cooling water temperature leaving the condenser than would plants with once-through cooling. Philadelphia Electric Company power plants with once-through cooling have an average condenser cooling water temperature of 55°F to 60°F during the coldest part of the year whereas the plants with cooling towers have a cooling water exit temperature of 80°F during the same period (Reference 9-1). Transferring heat from cooling water at 80°F to the ICES loop at 60°F by direct heat exchange would be possible, but the required heat exchange surface would be large.

By using a water-to-water heat pump to extract heat from the power plant cooling water, cooling water temperatures down to 40°F would be usable. In effect, the ICES central plant diesel driven air-to-water heat pumps would be replaced by water-to-water heat pumps located at the power plant site, and the overall ICES system performance would improve. If the peak heat rejection rate by the ICES system is significantly less than that of the power plant, it may also be feasible to reject heat from the ICES loop to the power plant cooling water and eliminate the cost of a separate heat rejection system.

No attempt was made to develop costs for this method of recovering waste heat. This method is very site specific and its merits will have to be evaluated for each proposed heat pump ICES site.

9.2.3 Waste Heat Utilization From On-Site Electricity Generation

On-site generation of electricity is another potential method of obtaining waste heat. Diesel engine prime mover generating systems have good electrical (~30%) and overall thermal efficiencies (~80%) (Reference 9-2). For each unit of electricity produced, approximately 1.67 units of heat can be recovered. Since the buildings in the community will use water-to-air heat pumps, there will be a need for electricity whenever there is a demand for heat. There will also be a non-heating related base electrical load. By generating electricity to meet the base load and the electric energy requirements of the water-to-air heat pumps, an on-site generating system would create enough waste heat to meet all of the ICES heat requirements. However, the ICES being considered cannot use the waste heat from the on-site generating system during the cooling season. Further, the waste heat available during much of the heating season would be in excess of the demand for such heat. On-site generation can only be competitive with electric utility power when the demand for waste heat matches closely its availability. This would not be the case for the ICES system being considered. Consequently, on-site generation does not appear to be a practical alternative for obtaining waste heat unless an industrial or commercial establishment in the community could use the excess waste heat not required by the HP-ICES.

9.3 HP-ICES WITH ON-SITE COGENERATION

A possible HP-ICES variant is a cogeneration plant devoted exclusively to providing electrical and thermal energy to the community. The electrical energy would be used to power the distributed heat pumps, the reject heat from the generator prime mover (preferably a combustion turbine or coal fired power plant instead of a diesel engine in order to achieve better quality steam) would drive steam turbines to power the central plant. This would require a second electrical distribution system for the distributed heat pumps, separate from that of the electric utility distribution system. The separate cables for the two systems would result in high capital costs and, therefore, such a system does not appear to be attractive. It may be more feasible to power some of the central plant units electrically and others by steam turbines, with both electricity and steam generated in the cogeneration plant. This would complicate the control of the different units in the central plant since, in addition to the thermal requirements of the loop, the need to balance electrical and thermal power demands constitutes an additional constraint on the control system. The fuel efficiency of such a system appears to be comparable to or, at best, up to 10% better than that of the HP-ICES used in the main body of this report. The initial investment for and the complexity of the central plant, however, are considerably greater. Therefore this alternative does not appear to be attractive and was not investigated further.

9.4 ALTERNATIVE HEAT SOURCES AND SINKS

Ambient air is the primary heat source and sink for HP-ICES using diesel driven water-to-air heat pumps in the central plant to heat the HP-ICES loop and a cooling tower to cool the loop. The previous discussion has dealt with the desirability of using waste heat or heat from a cogeneration plant as an alternative heat source. Alternative heat sources include surface water and solar energy. Surface water could also be used as a heat sink during the cooling season.

9.4.1 Surface Water as a Heat Source and Sink

Under certain climatic and geographic conditions, the use of surface water as a heat source and/or heat sink may be more energy efficient and more economical than the use of ambient air. In a cold climate, a large body of water that never freezes may constitute a higher temperature heat source than ambient air. In the U.S., this applies to the Great Lakes region and, to a smaller extent, to the coast of Maine. It also applies to areas near large rivers, such as the northern Mississippi, the northern Missouri, the Ohio rivers, and their tributaries. The concept of using a large water source HP-ICES in Oslo, Norway is being investigated (Ref. 9-3). The heat source would be the ocean, approximately 3 miles away, which reaches a minimum temperature of 40°F. An onshore heat exchanger would transfer the ocean heat to an uninsulated fresh water loop feeding water source heat pumps in each of the high-rise apartment buildings connected to the loop. No cooling is provided in this system.

Alternately, there exist geographic and climatic conditions under which a water heat sink is available at lower temperature than that of ambient air. However, recently it is been recognized that the use of bodies of water as heat sinks in other than very cold climates is undesirable. Most states now have legislation prohibiting this practice or severely restricting it. Many existing (and virtually all new) steam electric power plants must use cooling towers to prevent any significant temperature rise in natural bodies of water. Although the amount of heat generated from the cooling load of a community is only a small fraction of that rejected from a large modern power plant, recent experience has shown that the appropriate authorities would not permit "small" heat dumps from such system any more than they would permit "large" heat dumps from power plants. For example, the Miami River, a tributary of the Ohio river in western Ohio, has reached temperatures as high as 110°F in the summer, partly as a result of being used as a heat dump by man (Ref. 9-4). If this occurs in a sizeable river flowing north of 39° latitude, it is easy to understand the general reluctance

to permit any heat rejection into rivers and lakes. This would also apply to the year-round use of a body of water as the heat source/sink for a HP-ICES. Even though the net thermal input or removal on an annual basis may be zero, the seasonal heat additions or withdrawals may be large enough to disturb the ecosystems in these rivers or lakes.

By 1970, many states had established 68°F as the maximum allowable temperature and from 0 to 5°F as the maximum allowable change in temperature for streams with cold-water fisheries. For warm-water fisheries, the corresponding values are from 83°F to 93°F, and from 4°F to 5°F, respectively (Ref. 9-5). Since then, these limits have generally been tightened and, in many cases, no increase in water temperature is permitted at a certain distance from the point of heat dump.

The ocean may be used as a heat sink in certain cases, although severe restrictions are being put into effect for power plants along the shallow shores of the Middle Atlantic States. The Calvert Cliffs plant on the Chesapeake Bay and the Oyster Creek plant along the New Jersey bay shore are examples of serious environmental objections to thermal discharges into the ocean or into bays connected to the ocean. Thus, it does not appear desirable to devote a large effort to exploring the technical and economic problems inherent in heat rejection into natural bodies of water, when it appears that large-scale uses of this heat sink will not be environmentally acceptable in the future. In a number of locations where environmental objections might not be raised, the average water temperature exceeds the average ambient air temperature, e.g., along portions of the Gulf of Mexico Coast and at Key West. Using the ocean as a heat sink in those areas is, therefore, technically inferior to using ambient air.

The beneficial uses of waste heat when discharged into bodies of water cannot be ignored. Experiments with increasing fishery yields are being made at a number of locations: Lake Michigan, Long Island, Texas Gulf coast (the latter for increased shrimp yield). However, all of these experiments are being conducted at the condenser outfall of

thermal power plants which, for these base load plants, provides a fairly constant and reliable source of heat. The reject heat from a HP-ICES could not be used for such purposes, because its amount greatly depends on the weather and is therefore not suitable for improving the environment of aquatic life.

9.4.2 Solar Energy as a Heat Source

The use of solar energy as a heat source for HP-ICES is very attractive from a performance standpoint with respect to both HP-ICES and the solar energy system. The relatively low temperature heat (60°F) required by HP-ICES can be supplied by flat plate solar collectors mounted in a low cost fixed array. The low solar collector operating temperature, with respect to the ambient temperature, will eliminate the need for double glazing on the solar collectors or selective surfaces absorber coatings, leading to reduced solar collector costs.

As with waste heat, the collected solar energy can only be used by HP-ICES during the heating season. During the summer, the solar energy system will be idle. The longer this summer idle period is, the less attractive solar energy will be from an economic standpoint. Consequently, the use of solar energy appears to be more attractive in northern climates where the cooling season is much shorter than the heating season.

Both HP-ICES and solar energy systems are capital intensive. If waste heat is available, the economic feasibility of using solar energy is doubtful. However, the use of solar energy may make HP-ICES feasible at locations in northern climates which do not have a waste heat source nearby.

9.5 ALTERNATIVES TO HP-ICES CENTRAL PLANT DIESEL DRIVEN HEAT PUMPS

The use of diesel driven heat pumps has been proposed as a means of heating the HP-ICES loop during the winter when an outside source of

waste heat is not available. A major disadvantage of this approach is the use of oil by the diesel engines. Two other methods for driving the central plant heat pumps using non-scarce energy resources are the use of electric motors to drive the central plant heat pumps or the use of an on-site coal fired steam plant to operate steam turbine driven heat pumps.

Electricity generated using coal or nuclear energy (relatively non-scarce resources as compared to oil) could be used to run the central plant heat pumps and main circulating pump. This would lead to a substantial reduction in installed cost (order of magnitude - \$500,000) but would also result in much higher annual energy costs and a higher life cycle cost.

An on-site coal fired steam plant could be used to produce 125 psig steam to run condensing turbines. The steam turbines would replace the diesel engines as prime movers for the heat pumps and main circulating pump. By adding the reject heat from the condenser to the HP-ICES loop, the required heat pump capacity would be reduced. However, the initial capital investment required for this system would be significantly higher than for a central plant with diesel engine prime movers.

The two alternatives to central plant diesel engine prime movers are technically feasible, but their economic feasibility will probably depend highly on site characteristics and was not evaluated as part of this study.

9.6 ALTERNATIVE PIPING MATERIALS FOR THE HP-ICES LOOP

The HP-ICES loop was assumed to be constructed using uninsulated schedule 40 steel pipe; however, due to the low temperatures and pressures within the loop, plastic or concrete pipe could also be used. According to the 1978 Dodge Manual for Building Construction Pricing and Scheduling, the installed cost for plastic pipe in the 1-inch to 6-inch diameter size range is about 30% less than the installed cost for equivalent sizes of steel pipe. Since one third of the HP-ICES piping cost

is for pipe in this size range, using plastic rather than steel pipe for small to moderate diameter piping mains and branches would reduce the total piping loop installed cost by \$870,000 or approximately 10%. It may also be possible to achieve savings by using concrete pipe for the large piping mains.

While the change in piping from the schedule 40 steel pipe to other materials may offer cost reductions in certain cases, the lack of long-term operating experience with other piping and, therefore, the inability to predict their useful life prevents the accurate determination of life cycle costs for such systems.

10. COMPONENT TESTING REQUIREMENTS

The HP-ICES studied uses state-of-the-art components and techniques in the design and operation of the central plant and HP-ICES user equipment. These techniques and components are widely used in many types of building heating and cooling systems. No further testing of this equipment is necessary.

Further development and testing of Btu meters would be worthwhile. Btu meters are required to determine customer billing unless a flat service charge is used. Individual metering is preferred because it promotes energy conservation. It has been found that converting apartment houses from a single master meter to individual meters for each apartment reduces energy consumption by up to 25% (Ref. 3-1).

Various aspects of Btu metering with respect to HP-ICES are discussed in Section 3 including the lack of suitable meters. One unit was identified which could be modified to meet the needs of HP-ICES, but would cost approximately \$2800 per unit. This is higher than the cost of residential HP-ICES user equipment. At a cost of \$2800 per meter, the cost of the meters could represent a significant fraction of the total HP-ICES cost. Therefore, further development and testing is required to find an effective and low-cost method of metering HP-ICES customers.

HP-ICES loop piping costs are a significant fraction of the total HP-ICES cost. Any testing that would demonstrate a method of accomplishing this at lower cost would be of great benefit in advancing the cost effectiveness of the HP-ICES concept.

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11. DESCRIPTION OF ANALYSES

11.1 DESCRIPTION OF REFERENCE COMMUNITY

11.1.1 Introduction

The major difficulty that arose in attempting to define a reference community for this HP-ICES study was that there is no such thing as a typical community. Not only do residential construction practices vary with climate throughout the United States, but the fraction of land covered by buildings varies with geographical location (strangely enough, suburban building lots are generally smaller in the West than in the East) zoning codes, and occupant income. The mix of residential and non-residential buildings varies considerably from one community to another with no geographical or climatic pattern clearly discernible, and the definition of the portion of the community covered by the HP-ICES is somewhat arbitrary, even in a specific project.

Since it was deemed desirable to obtain "hard" engineering and economic data as early as possible in this project, it was decided to define a reference community in a relatively detailed manner and to employ a sensitivity analysis to evaluate the effects which variations in the reference community would have on the results obtained.

The plans for the reference community were developed with the assistance of Mr. Richard G. Guenzel of the Korman Corporation to whom we are greatly indebted.

11.1. Land Use Pattern

An overall plan of the reference community is given in Figure 3-1. It is fairly representative of mixed communities currently being constructed in the Middle Atlantic region of the country. A list of the

buildings and the overall land use of the community is shown in Table 3-1.

In typical fashion, the community center is occupied by office buildings. A commercial corridor extends from the center to one corner of the rectangular community area where light manufacturing plants and the central HP-ICES plant are located. Low-rise apartments spread from this area toward the single-family residential districts. On either side of the community center are townhouses with schools nearby. A smaller commercial area is located in the corner opposite to that of the ICES plant. Single-family homes cover the remainder of the community land area. Churches and recreational areas are dispersed throughout the residential areas. The gross land area of the community is 856.5 acres (1-1/2 square miles), 25% of which is devoted to streets.

11.1.3 Residential and Working Populations

Assuming four occupants per single-family house, three per townhouse, and 2 and 1/3 per apartment, the total community population adds up to 10,000 people (see Table 3-1). Assuming two adults per dwelling unit, there are 6000 adults in this community. If 90% of the men work, and if 20% of the women in the single-family dwellings, 40% in the townhouses, and 60% in the apartments work, total community employment is 1350 men and 525 women for a total of 1875. If the ratios of working women increase to 25%, 50% and 80%, respectively, which may be in line with present trends for the end of this century, female employment would be 675 with a total employment of over 2000.

The estimated job requirements for offices, commercial, and industrial establishments in the community are 4500 (Table 3-1). Thus, this community requires some outsiders to work within its boundaries. The daytime population of the community is therefore estimated to be 12,000 to 13,000, accounting for the fact that some of the older school children may work part time.

A "purist" may argue that the community ought to be entirely self-contained, i.e., its working population should be equal to the fraction of the resident population that works. As a matter of fact, such communities practically do not exist anywhere in the United States. Experience has shown that, even at certain remotely located military, governmental, or industrial installations where community facilities have been constructed by the employer, many people who work in the community prefer not to live there but commute to work from their residences outside the community. This holds even more so for communities that spring up in suburban locations near large cities. Most of these communities, once they reach a critical size, attract shops and service industries which require non-resident workers.

On the other end of the spectrum are "strictly bedroom" communities like the original Levittown on Long Island, New York or Restons, VA. Such communities are, however, not prime candidates for HP-ICES, as is shown in this report.

Therefore, it seems appropriate that the reference community has a working population slightly larger than what could be obtained from community residents alone.

11.2 BUILDING THERMAL ANALYSIS

11.2.1 Building Heating and Cooling Load Curves

Figures 11-1 through 11-10 estimate the net heating and cooling loads for the ten types of buildings in the reference community as would be seen by the HP-ICES loop. Both occupied and unoccupied heating are shown for schools, offices, and commercial buildings. Only unoccupied heating loads are shown for light manufacturing, churches and recreation centers since it is generally characteristic of these types of buildings that the internal gains during occupied periods provide all of the heat necessary. Cooling for nonresidential buildings was assumed to be required only during occupied hours.

Fig. 11-1

LOAD CHARACTERISTICS

Single Family Residence

HEAT FROM 'LOOP' = 0.64 factor × HEATING
 HEAT TO "LOOP" = 1.35 factor × COOLING
 Kwh(Owner) = .089 watts/BTU-HEATING
 = .102 watts/BTU-COOLING

Fig. 11-2

LOAD CHARACTERISTICS

Townhouses

HEAT FROM "LOOP" = 0.64 factor * HEATING
 HEAT TO "LOOP" = 1.35 factor * COOLING
 kWh (Owner) = .089 watts/BTU · HEATING
 .102 watts/BTU · COOLING

Fig. 11-3. LOAD CHARACTERISTICS

Apartments

HEAT FROM "LOOP" = 0.64 factor x HEATING
 HEAT TO "LOOP" = 1.35 factor x COOLING
 Kwh (Owner) = .089 watts/BTU - HEATING
 .102 watts/BTU - Cooling

Fig. 11-4

LOAD CHARACTERISTICS

Elementary School

$$\begin{aligned}
 \text{HEAT FROM "LOOP"} &= .80 \text{ factor} \times \text{HEATING} \\
 \text{HEAT TO "LOOP"} &= 1.25 \text{ factor} \times \text{Cooling} \\
 \text{Kwh(Owner)} &= 0.65 \text{ watts/Btu - HEATING} \\
 &= 0.68 \text{ watts/Btu - Cooling}
 \end{aligned}$$

Fig. 11-5. LOAD CHARACTERISTICS

Secondary School

HEAT FROM "LOOP" = 0.80 factor x HEATING
 HEAT TO "LOOP" = 1.25 factor x Cooling
 Kwh (Owner) = 0.65 watts/BTU - HEATING
 0.68 watts/BTU - COOLING

Fig. 11-6.

LOAD CHARACTERISTICS

Office Building

HEAT FROM "LOOP" = 0.80 factor $\times$ HEATING
 HEAT TO "LOOP" = 1.25 factor $\times$ COOLING
 Kwh (Owner) = 0.65 watts/BTU - HEATING
 0.68 watts/BTU - COOLING

Fig. 11-7. LOAD CHARACTERISTICS

Light Manufacturing

$$\begin{aligned}
 \text{HEAT FROM "LOOP"} &= 0.80 \text{ factor} \times \text{HEATING} \\
 \text{HEAT TO "LOOP"} &= 1.25 \text{ factor} \times \text{COOLING} \\
 \text{Kwh (Owner)} &= 0.65 \text{ watts/BTU - HEATING} \\
 &= 0.68 \text{ watts/BTU - COOLING}
 \end{aligned}$$

Fig. 11-8. LOAD CHARACTERISTICS

Commercial

HEAT FROM "LOOP" = 0.80 factor x HEATING
 HEAT TO "LOOP" = 1.25 factor x COOLING
 Kwh (Owner) = .065 watts/BTU - HEATING
 = .068 watts/BTU - COOLING

Fig. 11-9.

LOAD CHARACTERISTICS

Churches

HEAT FROM "LOOP" = 0.80 factor × HEATING
 HEAT TO "LOOP" = 1.25 factor × COOLING
 Kwh/(Owner) = .065 watts/BTU - HEATING
 .068 watts/BTU - COOLING

Fig. 11-10. LOAD CHARACTERISTICS

Recreational Centers

$$\begin{aligned}
 \text{HEAT FROM "LOOP"} &= 0.80 \text{ Factor} \times \text{HEATING} \\
 \text{HEAT TO "LOOP"} &= 1.25 \text{ factor} \times \text{COOLING} \\
 \text{Kwh (Owner)} &= .065 \text{ watts / BTU - HEATING} \\
 &= .068 \text{ watts / BTU - COOLING}
 \end{aligned}$$

The heating and cooling loads are characterized as net values, because it is assumed that buildings, other than single family residences or townhouses, would use type B or C heat pumps as described in Section 3. These units have the capability of transferring excess heat from a building's core to its perimeter. Therefore the HP-ICES loop will only see the net load after this internal transfer takes place. The load characteristics shown in Figures 11-1 through 11-10 are based on Werden Associates' experience in the design of this type of equipment.

The information at the bottom of Figures 11-1 through 11-10 was used to determine the performance of HP-ICES user heat pumps and is based on the average of the performance data for several commercially available heat pumps (Ref. 5-2 and 5-3).

It was assumed that buildings using the conventional system would not employ type B or C heat pumps. Consequently, there would be no internal transfer of heat. Therefore, additional heating would be required during occupied hours. Based on a projection of the internal loads not being used as a heat source by the conventional system, it was estimated that the additional heating required would be 15% of the annual heating load for apartments and 70% of the annual occupied hours heating load for schools, offices and light manufacturing buildings.

11.2.2 Building Heating and Cooling Load Calculations

Building heating and cooling loads were calculated for the reference community using the heating and cooling load curves in Figures 11-1 through 11-10, hourly Philadelphia dry bulb temperatures for 1968, and the building occupancy profiles in Table 11-1. The year 1968 was chosen because it is representative of the average Philadelphia weather both in the heating and cooling seasons.

The annual heating and cooling loads for the various buildings in the reference community with HP-ICES and with the conventional system are shown in Table 11-2. Note that for other than single family residences or townhouses, the heating loads for buildings in the conventional

Table 11-1. Reference Community Building Occupancy

<u>Building Type</u>	<u>Occupancy</u>	
Single Family Detached House	24 hr/day	
Town House	24 hr/day	
Apartments	24 hr/day	
Elementary School*	M-F	8am - 4 pm
Secondary School*	M-F	8am - 4 pm
Office Buildings	M-F	8am - 6 pm
Light Manufacturing	M-F	7am - 4 pm
Commercial	M,W,F,Sat.	9am - 9 pm
	T,Th.	9am - 5 pm
	Sun.	Closed
Churches	Sun.	8am - 2 pm
Recreation Centers	M-F	5pm - 10 pm
	Sat.,Sun.	9am - 5 pm

*School year was assumed to be 180 days with a two-week Christmas vacation and one-week spring vacation.

system will be greater than the loads for buildings connected to HP-ICES by the amount of internal heat transfer accomplished by HP-ICES type B and C user heat pumps.

11.2.3 HP-ICES and Conventional System User Annual Energy Requirements

Using the heating and cooling loads from Table 11-2 and the equipment performance factors from Figures 11-1 through 11-10, the annual energy requirements of HP-ICES users were calculated and are shown in Table 11-3.

The conventional systems used in this study are shown in Table 11-4. As explained in Section 5, these performance factors (COP's) are estimated values but it is believed they are reasonable for this type of equipment.

Table 11-2. Building Heating and Cooling Loads (10^6 Btu/Yr)

Building Type	HP-ICES System				Conventional System			
	Heating		Cooling		Heating		Cooling	
	Load	Energy	Load	Energy	Load	Energy	Load	Energy
Single Family Houses	106600	32380	14800	5152	106600	53300	14800	6167
Townhouses	20140	6118	2881	1003	20140	10070	2881	1200
Apartments	22170	7745	2575	896	25496	25496	2575	990
Elementary School	808	179	152	35	945	1575	152	52
Secondary School	1346	299	254	59	1573	2622	254	88
Offices	6273	1491	3745	869	8525	14208	3745	1291
Light Manufacturing	4430	983	9402	2182	4430	7383	9402	3242
Commercial	5099	1131	10160	2358	7426	12377	10160	3503
Churches	353	78	42	10	353	588	42	14
Recreation Centers	292	65	428	99	292	487	428	148

Table 11-3. HP-ICES and Conventional System
User Annual Energy Requirements

Building Type	HP-ICES Users Electricity 10 ⁹ Btu/Yr	Conventional System Users	
		Electricity 10 ⁹ Btu/Yr	Oil 10 ⁹ Btu/Yr
Single Family Residences and Townhouses	44.7	70.7	-
Apartments, Offices and Commercial Buildings	14.5	31.3	26.6
Light Manufacturing	3.2	3.2	7.4
Schools, Churches, and Recreation Centers	0.8	0.3	5.3
TOTALS	63.1	105.6	39.2

Table 11-4. CONVENTIONAL SYSTEMS

BUILDING TYPE	Equipment Performance Factors		
	HEATING/COOLING SYSTEM	HEATING COP	COOLING COP
Single Family House	Air-to-Air Heat Pump	2.0	2.4
Townhouses	Air-to-Air Heat Pump	2.0	2.4
Apartments	Resistance heaters/package "through-the-wall" air conditioner	1.0	2.6
Schools, Offices, Light Manufacturing, Commercial, Churches, Recreation Centers	Oil Fired Boiler/central conditioning	0.6	2.9

The conventional system annual energy requirements shown in Table 11-3 were calculated using the heating and cooling loads in Table 11-2 and the equipment performance factors in Table 11-4.

11.3 HP-ICES CENTRAL PLANT THERMAL PERFORMANCE

11.3.1 Diesel Engine Performance Characteristics

Large diesel engines suitable for continuous duty are available from several manufacturers including Caterpillar, Cummins and Detroit Diesel. This study is based on a Caterpillar model D399-SCAC-85 Stationary Diesel Engine. The unit has a rating of 1125 H.P. at 1200 rpm. Although the unit can be intermittently operated at higher speeds, because this Heat Pump ICES System is equivalent to a utility system, a maximum of 1200 rpm has been selected for a continuous duty rating for long life and low maintenance. The potential for heat recovery from a diesel engine based on Caterpillar data is shown in Table 11-5.

Table 11-5. Diesel Engine Heat Recovery

<u>Source</u>	<u>Heat Equivalent % of Shaft H.P.</u>
Jacket Water Recovery	68.1%
Exhaust Heat Recovery	55.3%
Turbosupercharger After-Cooler Heat Recovery	17.2%
Total	140.6%

11.3.2 Centrifugal Compressor Characteristics

The estimated performance of a compressor with a two-stage impeller as manufactured by York is shown in Table 11-6. The compressor is of such construction and displacement volume - 7500 cfm nominal - that refrigerant R-12 was selected. This size compressor was picked in order to generally match the prime mover capacity of the majority of available stationary diesel engines.

Table 11-6. Centrifugal Compressor Characteristics
Based on York #238A Two-stage R-12
Centrifugal - 7500 CFM (nominal)

Evaporator Temp. °F	Compressor Speed RPM	Evaporator Tons	Brake Horsepower
-20°	5856	800	1154
-10°	5212	720	994
0°	4802	640	765
10°	4392	560	615
20°	(4392)	480	(615-hot gas)

Table 11-6 tabulates the performance of the compressor as to evaporator temperature, reduced speed increments, evaporator tons, and brake horsepower (all at 65°F condensing temperature).

11.3.3 Diesel Driven Heat Pump Characteristics

The estimated heat pump characteristics are shown in Table 11-7 as a function of evaporator temperature. The evaporator capacity (Line 1) and the prime mover brake horsepower (Line 2) are taken from Table 11-6. The values in Lines 3 and 4 are the energy equivalent of Lines 1 and 2, respectively. The heat recovered from the diesel (Lines 5, 6 and 7) represents a percentage of the values in Line 4 as determined from Table 11-5. The fuel input to the diesel is shown in Line 9.

11.3.4 Outdoor Air Unit Performance Characteristics

Figure 11-11 shows the characteristics typical of outdoor air unit refrigerant coils at various outdoor temperatures entering the face of the coils versus evaporator temperature, with the resultant evaporator capacity measured in 10^6 Btu/hr. Typical outdoor air unit coil face area is of approximately 100 square feet with 50,000 cfm across the coil at a nominal 500'/min. face velocity. The performance shown in the curves

TABLE 11 - 7 ESTIMATED DIESEL DRIVEN HEAT PUMP CHARACTERISTICS

LINE	EVAPORATOR TEMPERATURE	-20°	-15°	-10°	-5°	0°	5°	10°	15°	20°
1	Required Capacity (tons)	800	760	720	680	640	600	560	520	480
2	Brake Horsepower	1154	1074	994	879	765	690	615	615	615
3	Energy Input at the Evaporator - BTU x 10 ⁶	9.6	9.12	8.64	8.16	7.68	7.2	6.72	6.24	5.76
4	Heat of Compression - BTU x 10 ⁶	2.93	2.73	2.53	2.24	1.95	1.76	1.57	1.57	1.57
5	Heat Pump Engine Jacket Heat Recovery - BTU x 10 ⁶	2.0	1.86	1.72	1.53	1.33	1.2	1.07	1.07	1.07
6	Heat Pump Engine Exhaust Heat Recovery - BTU x 10 ⁶	1.62	1.51	1.4	1.24	1.08	0.97	0.87	0.87	0.87
7	Heat Pump Engine After-Cooler Heat Recovery - BTU x 10 ⁶	0.5	0.47	0.44	0.39	0.34	0.30	0.27	0.27	0.27
8	Total (3-7)	16.65	15.69	14.73	13.56	12.38	11.43	10.5	10.02	9.54
9	Fuel Input - BTU x 10 ⁶	8.79	8.19	7.59	6.72	5.85	5.28	4.71	4.71	4.71

Figure 11-11. Estimated Performance for a Typical Outdoor Air Unit with a 10 HP Fan and 100 sq. ft. Face Area

may be considered conservative in that they indicate sensible heat capacity only. Some latent work would also be performed by the coils, resulting in a higher total enthalpy (evaporator capacity).

11.3.5 HP-ICES Central Plant Performance

11.3.5.1 0% Waste Heat Utilization

Table 11-8 shows the multiple heat pump performance and operation of the central plant for 10° increments of outdoor temperature. The number of heat pump compressor units and outdoor air fan/coil units has been optimized for the lowest energy consumption for each increment of outdoor temperature. For instance, a given heat pump compressor can be operated at various evaporator temperatures regardless of outdoor temperature to produce different evaporator tons. But, the lower the evaporator temperature, the fewer outdoor fan/coil units required, thereby reducing outdoor air fan horsepower.

Referring to Table 11-8, Line 1 indicates the annual hours occurrence for each 10°F increment of outdoor temperature. Line 2 indicates the heating load (or heating capacity) required in the aggregate by all HP-ICES users in the community. Line three gives the total heat input to the loop by the main circulating pump including the kinetic energy imparted to the loop and recovered heat from the diesel prime mover. The fuel required by the circulating pump is shown in Line 4. Line 5 represents the net heat load as seen by the central plant and is equal to Line 2 minus Line 3. Line 6 shows the energy available from each heat pump based on the selection of an evaporator temperature which minimizes energy consumption. The number of heat pumps required (Line 7) is equal to Line 5 divided by Line 6. Line 8 is the energy extracted from ambient air by the heat pump evaporator and is taken from Line 3 in Table 11-7. The total energy extracted from ambient is given in Line 9. The information in Line 10 is obtained from Figure 11-11. Line 11 gives the total number of fan units required and is equal to Line 9 divided by Line 10. The fuel required per heat pump is taken from

TABLE 11-8 HEAT PUMP - ICES CENTRAL PLANT PERFORMANCE * (NO WASTE HEAT AVAILABLE)

LINE	OUTDOOR TEMP. °F	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
1	Annual Hours - Ref. Community	0	134	528	973	1290	1383	1079	1387	1132	261	7
2	Energy Req'd. from HP-ICES Plant **	74.0	53.6	43.5	33.6	22.6	12.2	2.6	-5.15	-28.27	-68.5	-79.0
3	Energy added to HP-ICES Loop by circulating pump	0	2.2									
4	Fuel req'd. by circulating pump	0	2.7									
5	Net energy req'd by HP-ICES Loop (2-3)	0	51.4	41.3	31.4	20.4	10.0	0.4	0	0	0	0
6	Energy Avail. from each diesel heat pump/evaporator temp. (°F)	0	16.65/-20°	13.56/-5°	11.43/+5°	11.43/+5°	10.2/+10°	0	0	0	0	0
7	No. of Heat Pumps req'd (5÷6)	0	3.09	3.03	2.75	1.78	1.0	0	0	0	0	0
8	Energy extracted from ambient air per Heat Pump Evaporator	0	9.6/-20°	8.16/-5°	7.2/+5°	7.2/+5°	6.72/+10°	0	0	0	0	0
9	Total energy extracted from ambient air (7x8)	0	29.66	24.72	19.8	12.81	6.72	0	0	0	0	0
10	Energy extracted from ambient air per Fan Unit	0	.99/-20°	.755/-5°	.755/+5°	.628/+5°	.622/+10°	0	0	0	0	0
11	No. of Fan Units Req'd (9÷10)	0	32	33	26	10	6	0	0	0	0	0
12	Fuel req'd. per Heat Pump	0	8.79	6.72	5.28	5.28	4.71	0	0	0	0	0
13	Total Fuel req'd by Heat Pumps (7x12)	0	27.16	20.36	14.52	9.4	4.71	0	0	0	0	0
14	Total Fan Energy	0	.81	.84	.66	.25	.15	0	.38	.51	.64	.64
15	Total Energy req'd by Heat Pumps including Fans	0	27.97	21.2	15.18	9.65	4.86	0	0	0	0	0
16	Central Plant Performance Factor (5÷15)	0	1.84	1.75	2.07	2.11	2.06	-	-	-	-	-

* Energy units are Btuh x 10⁶

** Negative values indicate the quantity of heat removed from the loop by the cooling tower

Line 9 of Table 11-7. Total heat pump fuel is shown in Line 12. Line 14 shows total fan energy based on the requirement of a 10-horsepower fan per fan unit. The total heat pump energy requirement including fans is shown in Line 15 and the central plant performance factor (Line 5 divided by Line 15) is given in Line 16.

11.3.5.2 50% Waste Heat Utilization

The central plant performance for the case of 50% waste heat utilization is shown in Table 11-9. The description of Table 11-8 for the case of 0% waste heat utilization also applies to Table 11-9. Comparing Line 3 in Table 11-8 and 11-9, it can be seen that the values in Line 3 of Table 11-9 are less than those in Table 11-8 by a factor of 50% due to the availability of waste heat.

11.3.5.3 100% Waste Heat Utilization

The performance of the central plant with 100% waste heat utilization is shown in Table 11-10. It can be seen that when 100% waste heat is available no heat pumps are required. The only energy use is for operating the main circulating pump and the cooling tower fans.

11.3.5.4 Central Plant Performance During the Cooling Season

When the ambient temperature is 70°F or above, heat must be extracted from the loop by the central plant cooling tower. In Line 2 of Tables 11-8, 11-9, 11-10, the quantity of heat extracted from the loop is indicated as a negative value. During the cooling season, energy is required to run the main circulating pump and the cooling tower fans.

11.4 HP-ICES PIPING LOOP HEAT LOSS

The heat loss from the HP-ICES loop was estimated as follows:

$$Q = \frac{Kg \ 2 \ \pi \ L}{\cosh^{-1} (2Z/D)} (T_f - T_a) \quad (\text{Ref. 11-6})$$

TABLE 11-9 HEAT PUMP - ICES CENTRAL PLANT PERFORMANCE* (50% WASTE HEAT AVAILABLE)

LINE	OUTDOOR TEMP. °F	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
1	Annual Hours - Ref. Community	0	134	528	973	1296	1363	1679	1387	1132	261	7
2	Energy Req'd. from HP-ICES Plant**		26.8	16.7	6.8	0	0	0	-5.15	-28.27	-68.5	-79.0
3	Energy added to HP-ICES Loop by circulating pump		2.2	—	—	—	—	—	—	—	—	→
4	Fuel req'd. by circulating pump		2.7	—	—	—	—	—	—	—	—	→
5	Net energy req'd by HP-ICES Loop (2-3)		24.6	14.5	4.6	0	0	0	0	0	0	0
6	Energy Avail. from each diesel heat pump/evaporator temp.		16.65/ -20°	13.54/ -5°	10.5/ +10	0	0	0	0	0	0	0
7	No. of Heat Pumps req'd (5÷6)		1.48	1.07	.44	0	0	0	0	0	0	0
8	Energy extracted from ambient air per Heat Pump Evaporator		9.6/ -20°	8.16/ -5°	6.72/ +10	0	0	0	0	0	0	0
9	Total energy extracted from ambient air (7x8)		14.2	8.13	2.96	0	0	0	0	0	0	0
10	Energy extracted from ambient air per Fan Unit		.94/ -20°	.755/ -5°	.65/ +10	0	0	0	0	0	0	0
11	No. of Fan Units Req'd (9÷10)		15	12	5	0	0	0	0	0	0	0
12	Fuel req'd. per Heat Pump		8.79	6.72	4.71	0	0	0	0	0	0	0
13	Total Fuel req'd by Heat Pumps (7x12)		13.0	7.19	2.1	0	0	0	0	0	0	0
14	Total Fan Energy		.38	.31	.13	0	0	0	.38	.51	.64	.64
15	Total Energy req'd by Heat Pumps including Fans		13.38	7.5	2.23	0	0	0	0	0	0	0
16	Central Plant Performance Factor (5÷15)		1.83	1.93	2.06	—	—	—	—	—	—	—

* Energy units are Btuh x 10⁶

** Negative values indicate the quantity of heat removed from loop by the cooling tower

TABLE 11-10 HEAT PUMP - ICES CENTRAL PLANT PERFORMANCE* (100% WASTE HEAT AVAILABLE)

LINE	OUTDOOR TEMP. °F	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
1	Annual Hours - Ref. Community	0	134	528	973	1296	1363	1679	1387	1132	261	7
2	Energy Req'd. from HP-ICES Plant**	0	0	0	0	0	0	0	-5.15	-28.27	-68.5	-79.0
3	Fuel Req'd. by Circulating Pump	0	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
4	Total Fan Energy	0	0	0	0	0	0	0	.38	.51	.64	.64
5	Total Energy used by Central Plant	0	2.7	2.7	2.7	2.7	2.7	2.7	3.84	4.23	4.62	4.62

* Energy units are Btuh x 10⁶

** Negative values indicate the quantity of heat removed from the loop by the cooling tower

where:

Q = rate of heat transfer (Btuh)

K_g = thermal conductivity of the ground ($\frac{\text{Btu}}{\text{hr ft}^\circ\text{F}}$)

L = length of pipe (feet)

T_f = fluid temperature (°F)

T_a = ambient temperature (°F)

Z = depth of pipe centerline below the surface (feet)

D = pipe diameter (feet)

For this analysis, a fluid temperature of 60°F was used with an ambient temperature of 42°F, ground thermal conductivity of 0.6 Btu/(hr ft °F), and a five-foot ground cover over the pipes. The 42°F ambient temperature represents the average over the heating season in the climatic region for which the reference community HP-ICES was analyzed. The total pipe heat loss in the reference community during the heating season (heat loss given by the above equation times the number of hours in the heating season) was found to be equivalent to 12% of the heat extracted from the HP-ICES loop during the heating season. Two-thirds of the heat loss occurred in the small branch mains serving the residential areas of the reference community.

The reference community has a low energy density (peak heating demand per unit area). In more dense communities, the pipe heat loss would be less because of reduced pipe runs per customer. In this study it has been assumed that the HP-ICES loop piping is uninsulated. Insulating the pipe would reduce the heat loss but would add to the first cost of HP-ICES, and the loop piping is the predominant cost factor. Alternatively, the piping could be left uninsulated and waste heat used to compensate for pipe heat losses.

11.5 HP-ICES AND CONVENTIONAL SYSTEM USER EQUIPMENT INSTALLED AND OPERATING AND MAINTENANCE COSTS

The size of the heat pumps required by the single family residences and townhouses was estimated to be 2.5 tons and 1.5 tons respectively.

Estimated installed costs and annual operating and maintenance costs for air source heat pumps (conventional system) and water source heat pumps (HP-ICES) were obtained from References 11-1 and 11-2 respectively in 1976 dollars. These costs were escalated at a rate of 4% per year for equipment and 6% per year for maintenance to arrive at the 1980 costs and are shown in Table 11-11. A lower escalation rate was used for equipment because it is believed that the rapidly increasing market for heat pumps will tend to hold down their cost.

Average installed costs for conventional space conditioning equipment in other than single family residences in 1978 dollars were obtained from Reference 5-1. These costs were escalated at a rate of 6% per year to 1980 and are shown in Table 11-11.

For other than residential buildings, the conventional alternative was assumed to be an oil fired boiler and a central air conditioning system. In an HP-ICES community, these buildings would employ type B or C heat pumps as described in Section 3 and would not have to bear the cost of installing an oil fired heating system or cooling tower, but would have to pay for the incremental added cost of a double bundle condenser and a double bundle chiller. The HP-ICES user installed costs for non-residential buildings was determined by deriving deductions for the oil fired heating system and cooling tower, adding the cost of the double bundle condenser and chiller, and applying these factors to the conventional system costs. Based on heating and cooling system costs presented in Reference 11-3, it appears that the heating system cost in central systems can range from 10% to 45% of the total cost, with the lower percentage applying to high rise buildings. For this analysis a heating system deduct of 25% was used. A cooling tower deduction of 0.64 dollars per square foot of floor area was derived for light manufacturing and commercial, and a value of 0.48 dollars per square foot of floor area was derived for the other nonresidential buildings. These cooling tower deductions are based on the peak cooling loads shown in Table 3-2, cooling tower costs from Reference 11-4, and the assumption that cooling tower piping and wiring costs fifty-five dollars per ton of

cooling capacity. Information on the added incremental cost for double bundle condensers and chillers was obtained from Reference 11-5. The added cost for double bundle condensers is \$3.33 per thousand Btuh of heating capacity. The added cost for double bundle chillers is slightly higher at \$4.17 per thousand Btuh of cooling capacity. The added cost of the double bundle chillers and condensers per square foot of floor area is approximately \$0.27. The heating system and cooling tower deducts and the double bundle chiller and condenser add-on were applied to the conventional system costs to derive the HP-ICES user equipment costs shown in Table 11-11.

It can be seen in Table 11-11 that apartments have the lowest conventional system cost of non-single family buildings. It was assumed that this low cost as compared to other conventional system costs could not be for a central heating/cooling system. Therefore, no deductions were made to this cost, but the add-on for the double bundle chiller and condenser was applied to arrive at the HP-ICES cost for apartment buildings.

As mentioned previously, operation and maintenance (O&M) costs for residential conventional and HP-ICES equipment were obtained from References 11-1 and 11-2. The conventional system O&M costs in 1980 for single-family houses and townhouses are \$190 and \$148 respectively. The HP-ICES O&M costs are the same as for the conventional system users.

In Reference 11-3, O&M costs in 1976 dollars of \$14/boiler horsepower and \$14/ton of cooling capacity are given for boilers and air conditioning systems, respectively. These values were escalated to 1980 costs at a rate of 6% per year and used in the economic analyses for the HP-ICES and conventional system users. The O&M costs for residential HP-ICES and conventional system users are identical, but nonresidential HP-ICES users will have lower O&M costs than their conventional system counterparts because no boiler maintenance is required.

The total installed costs in 1980 for HP-ICES user equipment is $\$9.3 \times 10^6$ as compared to $\$12.4 \times 10^6$ for conventional system equipment.

HP-ICES O&M costs in 1980 are also lower at $\$500 \times 10^3$ as compared to $\$659 \times 10^3$.

Table 11-11. HP-ICES and Conventional System User Equipment Costs

Building Type	HP-ICES Equipment Costs 1980 dollars	Conventional System Equipment Costs 1980 dollars
Single Family Residences	2064/dwelling unit	2879/dwelling unit
Townhouses	1450/dwelling unit	1818/dwelling unit
Apartments	2.18/ft ²	1.80/ft ²
Elementary School	3.28/ft ²	4.74/ft ²
Secondary School	3.60/ft ²	5.19/ft ²
Offices	4.96/ft ²	6.97/ft ²
Light Manufacturing	2.89/ft ²	4.45/ft ²
Commercial Buildings	2.18/ft ²	3.37/ft ²
Churches	2.53/ft ²	3.70/ft ²
Recreation Centers	2.36/ft ²	3.46/ft ²

11.6 HP-ICES CENTRAL PLANT AND LOOP PIPING COST ESTIMATE

11.6.1 Summary

The total capital costs for the central plant and loop piping as well as the estimated engineering and design costs are shown in Table 11-12 for HP-ICES with 0%, 50%, and 100% waste heat utilization. It can be seen that loop piping is the predominant capital cost component in all cases and is independent of the quantity of waste heat utilized. The cost of the central plant decreases as more waste heat is utilized.

Table 11-12. - TOTAL ICES SYSTEM COST ESTIMATE -

	1	2	3	4	
	07.	507.	1007.		
	WASTE HT.	WASTE HT.	WASTE HT.		
1					1
2	LOOP PIPING	6935254 -	6935254 -	6935254 -	2
3					3
4	CENTRAL UTILITY PLANT	3499673 -	3049206 -	1358544 -	4
5					5
6	SUB-TOTAL	10434927 -	9984460 -	8293194 -	6
7					7
8	ENGINEERING-DESIGN 87.	834794 -	198756 -	663503 -	8
9					9
10					10
11	<u>EST. TOTAL PROJECT COST</u>	<u>11269721 -</u>	<u>10783216 -</u>	<u>8957297 -</u>	11
12					12
13					13
14					14
15					15
16					16
17					17
18					18
19					19
20					20
21					21
22					22
23					23
24					24
25					25
26					26
27					27
28					28
29					29
30					30
31					31
32					32
33					33
34					34
35					35
36					36
37					37
38					38
39					39
40					40

11.6.2 Loop Piping Cost Estimate

The cost of a typical branch main was estimated based on the layout in Figure 3-2. This cost was then converted to a per acre unit cost to arrive at branch main costs for single-family residences, townhouses, and apartments. Schools and light manufacturing buildings were assumed to be remote from the HP-ICES mains, and their individual branch piping costs were estimated. Other types of buildings such as offices, commercial establishments, churches and recreation centers were assumed to be located on main street arteries where they would tap directly into the HP-ICES mains.

The costs for the large distribution main loops shown in Figure 3-1 were estimated separately as were the central plant mains.

The piping was assumed to be installed in excavated trenches below streets prior to final paving, and the costs were estimated accordingly. Piping cost estimates are shown in Table 11-13.

Cost estimates were based on unit figures taken from:

- a. "Building Construction Cost Data - 1978, 36th Annual Edition" Robert Snow Means Company, Inc. and
- b. "1977 Dodge Manual for Building Construction Pricing and Scheduling", McGraw-Hill Information Systems Company.

11.6.3 Central Plant Cost Estimates

For the case where 0% waste heat is available, four heat pump systems and two main loop pumps were included in the cost estimate with one heat pump and one loop pump being standby units. For the HP-ICES with 50% waste heat utilization, three heat pumps were included in the cost estimate (one for standby) and two main loop pumps. In addition, two 400-horsepower boilers were included in the event the waste heat source was disrupted. The central plant in an HP-ICES with 100% waste heat utilization does not need any heat pumps, but still requires a main circulating pump and a standby unit. Two 800-horsepower boilers were

Table 11-13. LOOP-PIPING COST ESTIMATE-

page 1

		1	2	3	4
		UNIT COST	COMPONENT COST	PROJECT COST	
1	<u>Typical Branch Mains</u>				
2	500 LF 4" Sched. 40 Blk. Steel	12 ³⁶	6175 -		1
3	750 LF 3" " " " "	9 ¹⁰	6825 -		2
4	750 LF 2" " " " "	5 ¹²	4365 -		3
5	1000 LF Trenching	8 ³	830 -		4
6	1000 LF Back fill & Tamping	1 ³²	1320 -		5
7	(per 26 S.F. dwellings)		19515 -		6
8	Avg. Price / dwelling	780 ⁰⁰			7
9	Avg. Price / Acre	3120 ⁰⁰			8
10	1500 Dwellings Branch Mains	780 ⁰⁰	1,170,000 -	1,170,000 -	9
11	750 Town houses @ 6/acre.	520 ⁰⁰	390,000	390,000 -	10
12	750 Apartments @ 12/acre	260 ⁰⁰	195,000	195,000 -	11
13	1 Elem. School				12
14	1000 LF 4" Sched. 40 Blk. Steel	12 ³⁶	12350 -		13
15	500 LF Trenching	8 ³	415		14
16	500 LF Backfill & Tamping	1 ³²	660		15
17	1 Sec. School		13425	13425	16
18	1000 LF 6" Sched 40 Blk Steel	22 ²⁵	22250		17
19	500 LF Trenching	8 ³	415		18
20	500 LF Back fill & Tamping	1 ³²	660		19
21			23325	23325	20
22	<u>Office Bldgs (270,000 \$)</u>				21
23	No branches (fed from main)				22
24	<u>Eight Mfg' (320,000 \$)</u>				23
25					24
26	1200 LF 8" Sched 40 Blk. Steel	29 ⁴⁵	35340		25
27	600 LF Trenching	8 ³	498		26
28	600 LF Backfill & Tamping	1 ³²	792		27
29			36630	36630	28
30	<u>Commercial (300,000 \$)</u>				29
31	No branches (fed from main)				30
32	<u>Churches (30,000 \$)</u>				31
33	No branches (fed from main)				32
34	<u>Recreation (30,000 \$)</u>				33
35	No branches (fed from main)				34
36					35
37					36
38	<u>SUB-TOTAL</u>			1828380 -	37
39					38
40					39

LOOP PIPING COST ESTIMATE (cont'd)

page 2

1	2	3	4
UNIT COST	COMPONENT COST	PROJECT COST	

Brought Forward
Distribution Mains

1828380 -

13,400 LF. 18" Sched. 40 Blk. Steel

96.64 1294976 -

11,600 LF. 16" " " " "

72.98 846568 -

4,400 LF. 14" " " " "

63.20 277200 -

11,400 LF. 12" " " " "

48.00 547200 -

6,600 LF. 10" " " " "

42.40 279840 -

23,700 LF. Trenching

1.66 39342 -

23,700 LF. Backfill & tamping

2.64 62568 -

3347694

3347694 -

Utility Plant Mains

180 LF. 24" Sched. 40 Blk. Steel

145.76 99116 -

160 LF. 18" " " " "

96.64 15462 -

8 18" OS&Y Valves or B/F

950 - 7600 -

4 24" Butterfly (B/F)

2220 - 8900 -

2 24" Basket Strs. (BoxType)

5000 - 10000 -

130978

130978 -

TOTAL LOOP PIPING COST TO CONTRACTOR

5307052 -

CONTINGENCY 10%

530705 -

5837757 -

EST. CONTRACTOR OVERH'D. 10%

583775 -

6421532 -

EST. CONTRACTOR PROFIT 8%

513722 -

6935254 -

included as backup to the waste heat source. Central plant cost estimates are shown in Tables 11-14 through 11-16. Prices were secured from:

- a. Manufacturers indicated in the cost estimate forms
- b. "Building Construction Costs Date - 1978" (Means)
- c. "1977 Dodge Manual for Building Construction Pricing" (McGraw-Hill)
- d. (Prices not available from a, b, or c above were estimated by Werden Associates based on their experience).

11.7 HP-ICES CENTRAL PLANT ECONOMIC ANALYSIS

The following criteria were used in the economic analysis of each central plant scenario:

- Annual maintenance and insurance costs (other than labor) are 2% of the original central plant building and equipment cost
- Maintenance labor costs are \$121,600 in the first year of operation based on one chief engineer with a salary of \$25,000, four watch engineers at \$15,000 salary each and a clerk with a salary of \$10,000. Maintenance personnel were assumed to receive 28% fringe benefits
- Maintenance and insurance costs escalate at a rate of 5% per year
- Straight line depreciation is applied to the central plant and loop piping. The central plant equipment is depreciated over 20 years, the HP-ICES loop piping over 40 years, and the central plant building over 50 years
- There is no salvage value at the end of the equipment life
- 11% interest is charged on the loan for the installation of the central plant and loop piping (except for Case III, p.11-45)
- The property tax rate is 2.2% of the total installed cost for the central plant and loop piping
- The Federal income tax rate for the corporate owner/operator of the central plant and loop piping is 34%
- The Federal income tax rate of residential users is 30%
- The market discount rate used to determine the present worth of the annual costs from 1980 through 2000 is 7%.

The methodology applied in the economic analysis is largely based on the DOE publication of Reference 11-3.

Table 11-14. (0%). INDUSTRIAL WASTE AVAILABLE)
- CENTRAL UTILITY PLANT COST ESTIMATE - page 1

QUAN.	ITEM	UNIT COST	COMPONENT COST	PROJECT COST
1	1 BLDG. 7500 SQ. FT.	50 ⁰⁰ / ₁₀	375000 -	375000 -
2	2.1 AC. LAND (IND. ZONING)	75000 ⁷⁵⁰⁰⁰ / ₁₀₀₀	157500 -	157500 -
4	4 H/P SYSTEMS (BASED ON YORK #238 COMP. COMPLETE w/GEAR, CONDENSER, L.P. RECEIVER & LIQUID PUMP SETS)	155000 ¹⁵⁵⁰⁰⁰ / ₁₀₀	620000 -	
4	4 DIESEL PRIME MOVERS (BASED ON CATERPILLAR D399-SCAC-850, COMPL. w. Flywheel coupling & Heat exchangers)	115000 -	460000	
4	4 Exhaust Silencers	2000	8000	
4	4 Exhaust Stacks	1200	4800	
	Rigging, Field Erection of 4 H/P Systems	15000	60000	
	Rigging, Field Erection & alignment of 4 Diesel Prime Movers	10000	40000	
4	4 Foundations	3500	14000	
2	2 Main H ₂ O Loop Pumps (Based on Avrom 14x14x14-Made 1411)	14000	28000	
2	2 Pump Diesel Prime Movers (Based on Caterpillar D379-SCAC-850 compl. with Heat exchangers)	70000	140000	
2	2 Pump-Engine Foundations	2500	5000	
1	1 Air Compressor, Air Rec'r. (for cranking diesels)	6000	6000	
1	1 Air Compressor Foundation	1000	1000	
	SUB-TOTAL (LINES 4-40)		1386800	532500 -

Table 11-14 (Cont'd) (07% INDUSTRIAL WASTE AVAILABLE)
 -CENTRAL UTILITY PLANT COST ESTIMATE -

Page 2

		1 UNIT COST	2 COMPONENT COST	3 PROJECT COST	4
1	(BROUGHT FORWARD)		1386800 -	5325000 -	1
2					2
3	48 OUTDOOR AIR COIL BANKS	47 ⁸⁰ /SQ FT.	225600 -		3
4	2 100 SQ. FT. ea.				4
5	(Based on Trane Co.)				5
6	48 OUTDOOR AIR FANS & MOTOR				6
7	DRIVES (Based on Western				7
8	72'-VAX 73 #N 72 620	1147 ea.	55056 -		8
9					9
10	48 OUTDOOR AIR SHROUD-	1000 ea	48000 -		10
11	TRANSITIONS (Based on				11
12	Peabody & Wind)				12
13					13
14	48 Coil Bank Footings	500 ea.	24000 -		14
15					15
16	4 Sets liquid recirculating				16
17	refrigerant Mains				17
18	320' - 6"	22.45/LF	7184 -		18
19	320' - 4"	12.35/LF	3952 -		19
20	320' - 3"	9.10/LF	2912 -		20
21	960' - 2"	5.82/LF	5587 -		21
22	96 - 2" globe valves, w/strs.	210 ⁰⁰ ea.	20160 -		22
23					23
24	Refrigerant Charge, 88,400 ^{lb}	724/lb	49248 -		24
25					25
26	Insulation (shells, pipe, pumps)		40000 -		26
27					27
28	1 Central Control console		50000 -		28
29	w/microprocessor, et al.				29
30					30
31	2 20,000 gal. Diesel fuel tanks	6925 -	13850 -		31
32					32
33	2 Tank excav., pads, etc. piping	8000 -	16000		33
34					34
35	SUB-TOTAL (LINES 1-33)		1948349	1948349	35
36					36
37					37
38					38
39					39
40	SUB TOTAL			2488849 -	40

Table 11-14 (Cont'd) (O). INDUSTRIAL WASTE AVAILABLE
- CENTRAL UTILITY PLANT COST ESTIMATE -

page 3

1	2	3	4
UNIT COST	COMPONENT COST	PROJECT COST	

(BROUGHT FORWARD)

2480849-

Elec. wiring

O.A. FANS 480HP

50⁰⁰/HP

24000-

C.T. FANS - 3260HP

48⁰⁰/HP

7200-

C.T. CONTROL WIRING

500-

AIR COMPRESSOR 100HP

30⁰⁰/HP

3000-

CENTRAL CONSOLE

6000-

MISC. PUMPS & CONTROLS

6000-

SUB TOTAL (LINES 4-9)

46700-

46700-

1 COOLING TOWER - ERECTED
(BASED ON MARLEY
S-CELL) AVERAGED W/
B.A.C. - 3 CELL

150500-

SUB-TOTAL

CONTINGENCY * 10%

2678049

267804

2945853

294585

EST. CONTRACTOR OVERH'D 10%

3240438

EST. CONTRACTOR PROFIT 8%

259235

3499673

* KNOWN ITEMS (NOT IN EST.)

1. SILENCERS & STACKS

FOR H₂O PUMP DIESELS

Table 11-15. (507- INDUSTRIAL WASTE AVAILABLE)
- CENTRAL UTILITY PLANT COST ESTIMATE - page 1

QUAN	ITEM	1 UNIT COST	2 COMPONENT COST	3 PROJECT COST	4
1	1 BLDG - 6380 ^{sq} ft	50 ^{sq} /ft	319000 -	319000 -	1
2	1.8 AC. LAND (IND. ZONING)	75,000 ^{sq} /ac.	135000 -	135000 -	2
3					3
4	3 H/P SYSTEMS (BASED ON	155000 ^{ea}	465000 -		4
5	YORK #238 COMPRESSOR, COUPLING				5
6	W/ GEAR, CONDENSER, L.P.				6
7	RECEIVER & LIQUID PUMP SETS				7
8					8
9	3 DIESEL PRIME MOVERS	115000 ^{ea}	345000 -		9
10	(BASED ON CATERPILLAR				10
11	D399-SCAC-850, COMPL.				11
12	w/ Flywheel coupling &				12
13	Heat exchangers				13
14					14
15	3 Exhaust Silencers	2000 ^{ea}	6000 -		15
16					16
17	3 Exhaust Stacks	1200 ^{ea}	3600 -		17
18					18
19	Rigging & Field Erection	15000 -	45000 -		19
20	of H/P Systems				20
21					21
22	Rigging, erection &	10000 -	30000 -		22
23	alignment of Diesel Engines				23
24					24
25	3 Foundations	3500 -	10500 -		25
26					26
27	2 Main Loop H ₂ O Pumps	14000 -	28000 -		27
28	(Based on Aurora 14x16x180)				28
29					29
30	2 Pump Diesel Pump Prime	70000 -	140000 -		30
31	Movers (based on Caterpillar				31
32	D379-SCAC-850 compl.				32
33	w/ heat exchangers				33
34					34
35	2 Pump-Engine Foundations	2500 -	5000 -		35
36					36
37	1 Air Compressor, Air Receiver	6000 -	6000 -		37
38	(for cranking diesels)				38
39					39
40	1 Air Compressor Foundation	1000 -	1000 -		40
	SUB-TOTAL (LINES 4-40)		1088100 -	454000	

Table 11-15 (Cont'd) (507. INDUSTRIAL WASTE AVAILABLE)
CENTRAL UTILITY PLANT COST ESTIMATE. page 2

	1	2	3	4
	UNIT COST	COMPONENT COST	PROJECT COST	
1 (BROUGHT FORWARD)		1088100 -	454000 -	1
2				2
3 36 OUTDOOR AIR COIL BANKS	47 ⁰⁰ /ft	169200 -		3
4 @ 100 SQ. FT. EA.				4
5 (Based on Trane Co.)				5
6 36 OUTDOOR AIR FANS & MOTORS	1147 ea	41292 -		6
7 DRIVES (Based on Western				7
8 72"-VAX73#N 72620				8
9				9
10 36 OUTDOOR AIR SHROUD -	1000 ea	36000 -		10
11 TRANSITIONS (Based on				11
12 Peabody # Wind)				12
13				13
14 36 Coil Bank Footings	500 ea	18000 -		14
15				15
16 3 Sets of liquid recirculating				16
17 refrigerant Mains				17
18 240'-6"	2245/LF	5388 -		18
19 240'-4"	1225/LF	2964 -		19
20 240'-3"	910/LF	2184 -		20
21 720'-2"	522/LF	4190 -		21
22 72"-2" globe valves, w/strainers	210 ea	15120 -		22
23				23
24 Refrigerant Charge 51,300#	722/lb	36936 -		24
25				25
26 Insulation		30000 -		26
27				27
28 Central Control console		50000 -		28
29 w/micro processor, et al.				29
30				30
31 2 15000gal Diesel Fuel tanks	5420 -	10840 -		31
32				32
33 Tank excav., pads, piping, etc.	7000 -	14000 -		33
34				34
35 SUB-TOTAL (LINES 1-33)		1524214 -	1524214 -	35
36				36
37				37
38				38
39				39
40 SUB-TOTAL			1978214 -	40

Table 11-15 (Cont'd) (50% INDUSTRIAL WASTE AVAILABLE)
CENTRAL UTILITY PLANT COST ESTIMATE page 3

		1 UNIT COST	2 COMPONENT COST	3 PROJECT COST	4
1	(DROUGHT FORWARD)			1978214 -	1
2					2
3	<u>Elec. Wiring</u>				3
4	O.A. Fans 360 HP	50 ²² /HP	18000 -		4
5	C.T. Fans 3 @ 60 HP	40 ²² /HP	7200 -		5
6	C.T. CONTROL WIRING		500 -		6
7	AIR COMPRESSOR 100 HP	30 ²² /HP	3000 -		7
8	CENTRAL CONSOLE		6000 -		8
9	MISC. PUMPS & CONTROLS		6000 -		9
10	SUB-TOTAL (LINES 4-9)		40700 -	40700 -	10
11					11
12	1 COOLING TOWER - ERECTED				12
13	(BASED ON AVER. MARLEY & BAC)			150500	13
14					14
15	2 400 H.P. Low Press Boilers	28000 ea	56000 -		15
16	(Superior)				16
17	2 Sets Boiler Foundations,	21000 ea	42000 -		17
18	ftr, rigging, erection, stacks,				18
19	& all				19
20					20
21	1 20,000 gal. Boiler fuel oil	6925	6925 -		21
22	tank				22
23					23
24	1 Tank exc., pads, piping, etc	8000	8000 -		24
25	SUB TOTAL (LINES 15-24)		112925 -	112925 -	25
26					26
27					27
28					28
29	2 Steam-to-Loop H ₂ O heat exchangers	11500 -	23000 -		29
30	2 Sets Steam piping & specialties	8000 -	16000 -		30
31	2 Sets insulation	6000 -	12000 -		31
32	SUB-TOTAL (LINES 29-31)		51000 -	51000 -	32
33	SUB-TOTAL			2333339 -	33
34	CONTINGENCY - 10%.			2333339 -	34
35				2566672 -	35
36	EST. CONTRACTOR OVERH'D - 10%.			2566672 -	36
37				2823339 -	37
38	EST. CONTRACTOR PROFIT - 8%.			225867 -	38
39				3049206 -	39
40					40

Table 11-16. (100% INDUSTRIAL WASTE AVAILABLE)
CENTRAL UTILITY PLANT COST ESTIMATE - page 1

		1	2	3	4
QUAN.	ITEM	UNIT COST	COMPONENT COST	PROJECT COST	
1	1 BLDG 6000 sq FT.	50 ^{sq} /sq ft	300000 -	300000 -	1
2	.75 ACRE LAND (IND. ZONING)	75000/acre	56250 -	56250 -	2
3					3
4	2 Main H ₂ O Loop Pumps	14000 ea	28000 -		4
5	(Based on Aurora 14x16x18)				5
6					6
7	2 Pump Diesel Prime Movers	70000 ea	140000 -		7
8	(Based on Caterpillar D-379-				8
9	SCAC-850 complete with				9
10	heat exchangers				10
11					11
12	2 Pump-Engine Foundations	2500 ea	5000 -		12
13					13
14	2 Exhaust Silencers	2000 ea	4000 -		14
15					15
16	2 Exhaust Stacks	1200 ea	2400 -		16
17					17
18	1 Air Compressor for Diesel	5000	5000 -		18
19	Cranking w/air receiver, etc				19
20					20
21	1 Air Compressor Foundation	1000 -	1000 -		21
22					22
23	1 15000 gal Diesel fuel tank	5420	5420 -		23
24					24
25	- Tank excavation, pad, piping, etc	7000	7000 -		25
26	SUB-TOTAL (LINES 4-25)		197820	197820 -	26
27	1 COOLING TOWER, ERECTED		150500 -	150500 -	27
28	(Based on average of Marley & Oak)				28
29					29
30	2 800 HP Low Press Boilers	45000 ea	90000 -		30
31	(Based on Superior)				31
32	2 Sets, Boiler foundations, frt,	33750 ea	67500 -		32
33	rigging, erection, stacks, et al				33
34					34
35	1 20,000 gal Boiler fuel tank	6925 -	6925 -		35
36					36
37	1 Tank excavation, pad,	8000	8000 -		37
38	piping, etc.				38
39					39
40	SUBTOTAL (LINES 30-37)		112425		40
	SUBTOTAL			704510 -	

Table 11-16. (Cont'd) (100% INDUSTRIAL WASTE AVAILABLE)
CENTRAL UTILITY PLANT COST ESTIMATE - page 2

	1	2	3	4
	UNIT COST	COMPONENT COST	PROJECT COST	
(BROUGHT FORWARD)		172425	704576 -	1
STEAM PLANT		172425 -	172425 -	2
2 Steam-to-loop heat exchangers	15500	31000 -		3
2 Sets steam piping & specialties	12000	24000		4
2 Sets insulation	8000	16000		5
		71000	71000	6
Elec. wiring -				7
C.T. Fans - 3060 HP	40¢/HP	7200 -		8
Air Compressor 100 HP	30¢/HP	3000 -		9
CT. Control wiring		500		10
CENTRAL CONSOLE		6000		11
Misc. controls		6000		12
		22700	22700 -	13
1 CENTRAL CONTROL CONSOLE		50000	50000	14
w/micro processor, etc				15
SUB-TOTAL			1020695	16
CONTINGENCY - 10%			102069	17
EST. CONTRACTOR OVERHEAD 10%			1122764	18
EST. CONTRACTOR PROFIT 10% (smaller job)			112276	19
			1235040	20
			123504	21
			1358544	22

Life cycle costs were calculated for the HP-ICES central plant and loop piping over the twenty-year period from 1980 to 2000. The annual revenue required by the HP-ICES owner in year (n) was calculated using the following equation:

$$RR(n) = [(C_p(n) \times K_f) + \frac{C_p(o)}{L} + C_v(n)]$$

where:

- RR(n) = annual required revenue
- $C_p(o)$ = the total initial installed capital cost of the HP-ICES system
- $C_p(n)$ = the total undepreciated (straight-line) cost of the HP-ICES system
- K_f = the annual capital carrying charge factor
- $C_v(n)$ = the annual total variable costs of operating HP-ICES
- L = equipment life .

The total undepreciated (straight-line) cost of HP-ICES $C_p(n)$ was determined by:

$$C_p(n) = C_p(o) - \frac{(n-1)}{L} C_p(o)$$

and the annual capital carrying charge factor, K_f , is given by:

$$K_f = (I_d \times F_d) + I_e \frac{(1 - F_d)}{1 - T_i}$$

where:

- I_d = interest on debt
- F_d = fraction of capital supplied by debt financing
- I_e = rate of return on equity
- T_i = Federal income tax rate .

The annual total variable costs ($C_v(n)$) are composed of fuel costs, property taxes, overhead, maintenance, insurance, and labor costs.

Maintenance, insurance, and labor costs were assumed to escalate at 5% per year from 1980 through 2000. All 1980 base year costs were obtained by escalating 1978 costs to 1980 costs at 6% per year. The 1980 maintenance and insurance costs were assumed to be equal to 2% of original capital costs.

Fuel costs are composed of electric and oil costs. For the base line analysis, they were escalated from 1980 costs at 6.5% and 7% per year, respectively. Sensitivity analyses were carried out for 9% and 10% per year, and for 14% and 15% per year cost escalations, respectively.

The present value (PV) of any cost incurred in any year n is

$$PV = \frac{RR(n)}{1.07^n}$$

Summing annual present values over the 20-year life yields the total life cycle cost of the system.

The following values were used for the three ownership scenarios considered.

Case I - Profit making utility ownership of ICES:

- 50% equity financing
- 50% debt financing at 11%
- 9% rate of return on equity
- 2% property tax rate

Case II - Cooperatively owned ICES

- 100% debt financing at 11%
- zero rate of return on equity

Case III - Municipal ownership of ICES

- 100% debt financing at 6.5%
- zero rate of return on equity
- no property taxes

Central plant and loop piping life cycle costs are shown in Tables 11-17 and 11-18 as a function of waste heat utilization, type of ownership, and community energy density. It can be seen that HP-ICES would be most beneficial in communities where it was municipally owned, utilized waste heat to a significant extent, and the community was highly developed (i.e., had a high energy density).

Table 11-17 HP-ICES Central Plant and Loop Piping Life Cycle Costs (\$ x 10⁶)

Ownership	Percent Waste Heat Utilization		
	0%	50%	100%
Private Utility	34.3	30.2	25.9
Community Cooperative	32.8	28.7	24.6
Municipal Utility	27.7	23.7	20.2

Table 11-18 HP-ICES Central Plant and Loop Piping Life Cycle Cost as a Function of Waste Heat Utilization and Community Energy Density

Percent Waste Heat Utilization	Community Energy Density Based on Peak Heating Demand (10 ⁶ Btuh/acre)			
	0.119	0.268	0.537	0.805
0	34.3	30.3	28.3	26.7
50	30.2	26.2	24.2	22.6
100	25.9	22.0	20.0	18.4

11.8 SENSITIVITY ANALYSES

The sensitivity of HP-ICES economics was tested against type of ownership, community size, percent waste heat utilization, community energy density based on peak heating demand, energy cost escalation rates, and central plant maintenance personnel salary level. Most of these analyses have been discussed in sufficient detail in other sections of the report. In this section, the methodology used to test the effects of community size and energy density on HP-ICES economic feasibility are described.

11.8.1 Community Size

The effect of community size on HP-ICES economic feasibility was examined by calculating life cycle costs for HP-ICES in communities half and twice the size of the reference community. It was assumed that the new communities would have the same composition as the reference community and the HP-ICES loop network as shown in Figure 3-1 would remain the same except for a change in size. Because the community composition remains constant, the energy requirements of a community twice the size of the reference community would be twice the reference energy requirements. Similarly reducing the size of the reference community by one-half would halve its energy requirements.

Since the equipment in the central plant is modular, its cost was assumed to vary directly with system size. However, land and building costs and the cost of the central plant utility mains would more likely be subject to economics of scale. For a doubling in community size, it was assumed that central plant building, land and utility main costs would increase by a factor of 1.5, and halving the size of the reference community would reduce these costs to 75% of the reference community values.

As the size of the reference community changes, the length and diameter of the HP-ICES loop mains (piping shown in Figure 3-1) would change. As the size of the reference community changes, the length of

the loop mains will change by a factor equal to the square root of the ratio of the new community area to that of the reference community. For example, doubling community size will increase the length of the mains by the square root of two. The diameter of the mains, assuming they are sized based on the peak heating load, will change as the square root of the ratio of the new peak heating demand to the old peak heating demand (assuming the flow velocity is unchanged).

While some customers are connected directly to the HP-ICES loop mains, many others are supplied by branch mains. An example of branch main piping is shown in Figure 3-2. Branch main costs per dwelling unit for single family residences, townhouses and apartments are shown in Table 11-13. It was assumed these branch main costs per dwelling unit were independent of community size and the total branch main costs were directly proportional to the number of dwelling units.

Piping costs were estimated using unit pricing data from Reference 5-1. It was found that doubling the size of the reference community caused piping costs to increase by a factor of 2.18. Reducing the size of the reference community by one half reduced piping costs by a factor of 0.465. Thus, as the size of a community increases, the cost of piping increases at a slightly faster rate. Similarly, as a community decreases in size, piping costs decrease at a slightly faster rate.

The life cycle cost of the central plant in the community half the size of the reference community was 42% of the reference community central plant life cycle cost. In the larger community the life cycle cost of the central plant was 2.02 times as large as for the reference community. Considering the total HP-ICES life cycle cost (sum of the life cycle costs for the central plant and the users), reducing the reference community by one half reduced the life cycle cost to 46% of the reference community value. Doubling the size of the reference community increased the total life cycle cost by a factor of two. Based on these results, it was concluded that HP-ICES economic feasibility is relatively insensitive to community size.

11.8.2 Community Energy Density

The energy density of the reference community based on peak heating demand is 0.119×10^6 Btuh/acre whereas urban centers with high rise buildings can have energy densities greater than 0.97×10^6 Btuh/acre (Ref. 3-1). The sensitivity of HP-ICES economics to community energy density was evaluated by calculating HP-ICES life cycle costs for communities having energy densities of 0.268, 0.537, and 0.805×10^6 Btuh/hr. These energy densities are based on gross community area and correspond to energy densities of 0.3, 0.6, and 0.9×10^6 Btuh/acre based on the zoned area of the reference community (refer to Table 3-1).

In this analysis, as for the community size sensitivity analysis, it was assumed that community composition and the arrangement of the loop piping network were unchanged for communities with higher energy densities than the reference community. If the reference community were somehow reduced in size, its energy density would increase and loop piping would decrease in length, but pipe diameters would remain the same since the peak load was unchanged. Since the pipe diameters are unchanged, the cost of piping in the smaller community is equal to the cost of pipe in the reference community times the change in pipe length.

The reference community peak heating load (see Table 3-2) was divided by each of the three energy densities used in this analysis. In this manner, the areas to which the reference community would have to be reduced to achieve these densities were determined. The pipe length reduction factor for each energy density was found by taking the square root of the ratio of the corresponding reduced area to the reference community area. The reduced piping costs associated with each energy density were found by multiplying the appropriate pipe length reduction factor by the reference system loop piping cost given in Table 11-12.

Because the community composition has been assumed to remain constant, the energy requirements by the more dense communities would be the same as for the reference community. Therefore, the central plant

costs and energy usage for the dense communities would be identical to the reference community. Using the reference community central plant data and the reduced piping costs, central plant and loop piping life cycle costs were calculated. The results are shown in Table 11-18. It can be seen that HP-ICES economic feasibility is quite sensitive to community energy density.

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APPENDIX A: FUEL PRICES

The competitive fuels considered in this study were No. 2 heating oil, diesel fuel and residential, commercial and industrial electricity. The present prices of these fuels are shown below:

Table A-1. Present Fuel Prices

<u>Fuel</u>	<u>Reference</u>	<u>Fuel Price (\$/10⁶Btu)</u>	
Residential Fuel Oil	A-1	3.65 (1978)	*
No. 2 Diesel Fuel	A-2	3.20 (1978)	**
Residential Electricity	A-3	16.11 (1977)	***
Commercial Electricity	A-3	21.09 (1977)	†
Industrial Electricity	A-3	12.60 (1977)	††

*Average for first 4 month of 1978 for Mid Atlantic Region.

**Delivered price in suburban Philadelphia based on a tank car lot (6500 gallons). Price includes freight and state sales tax.

***Based on residential usage of 1000 kWh/month in Philadelphia exclusive of heating or air conditioning.

†Based on a commercial building in Philadelphia with 30 kW demand and 6000 kWh monthly usage.

††Energy cost for an industrial establishment with primary (high tension) service, a 300 kW demand and a 120,000 kWh monthly usage.

The economic analyses performed for this study used 1980 as the starting year. The fuel costs shown in Table A-1 were escalated at an annual rate of 8% (6% inflation + 2% real increase) to derive the 1980 fuel costs. After 1980, fuel oil costs were assumed to increase at the rate of 7% per year (5% inflation + 2% real increase) and electricity costs at a rate of 6.5% per year. Fuel costs at ten year intervals from 1980 to 2000 are shown in Table A-2.

Table A-2. Future Fuel Prices

Fuel	Fuel Price (\$/10 ⁶ Btu)		
	1980	1990	2000
Residential Fuel Oil	4.26	8.38	16.48
No. 2 Fuel Oil	3.73	7.34	14.43
Residential Electricity	18.79	35.27	66.21
Commercial Electricity	24.60	46.18	86.68
Industrial Electricity	14.70	27.59	51.80

The electricity prices do not include state and local taxes.

Sensitivity analyses were carried out in Section 6. One of the factors whose effect was analyzed was the fuel cost escalation rate. Table A-2 shows the rates used in the baseline analysis. Higher escalation rates whose effects were analyzed are shown in Section 6.

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