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Heat-Pump-Centered Integrated Community Energy Systems

System Development

Franklin Research Center Final Report

MASTER

**ENERGY AND ENVIRONMENTAL
SYSTEMS DIVISION**

ARGONNE NATIONAL LABORATORY

OPERATED FOR THE U. S. DEPARTMENT OF ENERGY
UNDER CONTRACT W-31-109-ENG-38

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Printed in the United States of America. Available from National Technical Information Service,
U. S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

HEAT-PUMP-CENTERED
INTEGRATED COMMUNITY ENERGY SYSTEMS
System Development
Franklin Research Center Final Report*

by

Richard E. Crane
FRANKLIN RESEARCH CENTER

and

Robert G. Werden, PE
R. G. WERDEN & ASSOCIATES

December 1979

Prepared for

Energy and Environmental Systems Division
Argonne National Laboratory
Under Argonne Contract No. 31-109-38-4547
Argonne Project Manager: James M. Calm, PE

Work sponsored by

U.S. DEPARTMENT OF ENERGY
Assistant Secretary for Conservation and Solar Energy
Office of Buildings and Community Systems
Community Systems Division
Community Systems Technology Branch

*This report supersedes ANL/ICES-TM-26: *Heat-Pump-Centered Integrated Community Energy Systems, System Development, Franklin Research Center Interim Report.*

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PREFACE

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

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

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

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

Heat-pump-centered integrated community energy systems (HP-ICES) are energy systems for communities which provide heating, cooling and/or

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

The report which follows 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 1984. The seven phases include System Development, Demonstration Design, Design Completion, HP-ICES Construction, Operation and Data Acquisition, HP-ICES Evaluation, and Upgraded Continuation.

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

The report which follows presents the findings in the development and analysis of one concept under investigation. This report was prepared by the Franklin Research Center. The principal author of this report was 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 Associates. The writers are indebted to Mrs. Miriam Foster for the careful preparation of the manuscript.

The authors wish to thank Mr. Jacinto F. Gammino, Executive Director of the Housing Authority of Phillipsburg, New Jersey, and Mr. Christopher Sutherst and Mr. Keith Snidtker of the Ingersoll-Rand Corp., Phillipsburg, New Jersey for their invaluable advice and assistance in the application of the HP-ICES concept to Heckman Terrace Annex.

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1. EXECUTIVE SUMMARY

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. When heat must be added to the common piping loop, this heat may be supplied by diesel driven air source heat pumps or boilers in the central plant, or by waste heat from industrial sources, (See Figures 3-1 and 3-2).

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.

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 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.

HP-ICES OWNERSHIP
P- PRIVATE M- MUNICIPAL

ENERGY ESCALATION RATES
(ELEC. RATE/OIL RATE)

Figure T-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 16% to 32% less resource energy than conventional systems during the heating season; at the times of the heating peak, the resource energy savings are 37% to 51%. 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 14% 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 between 0.6×10^{15} Btu and 1.3×10^{15} Btu.

In order to demonstrate the applicability of the above findings to specific sites, HP-ICES were designed for two existing communities, one in Phillipsburg, New Jersey, the other near Chicago, Illinois.

Heckman Terrace in Phillipsburg is a public housing development built in 1952. It consists of 24 6-unit apartment houses presently heated by a gas-fired central hot water heating plant. Using waste heat from a neighboring large industrial plant, the HP-ICES system would use the existing hot water distribution system to provide warm (65°F) water to 1000 heat pumps located in each room of the housing project.

Assuming continued availability of natural gas, conversion of this project to HP-ICES would be economically feasible compared to continuing the use of the present system.

If either natural gas would not be available and the boilers would have to burn fuel oil for which they are equipped, or if a water source heat pump with a seasonal performance factor of 4 were developed, the HP-ICES system would have a lower 20-year life cycle cost than the existing system.

If either natural gas would not be available and the boilers would have to burn fuel oil for which they are equipped, or if a water source heat pump with a seasonal performance factor of 4 were developed, the HP-ICES system would have a lower 20-year life cycle cost than the existing system.

The mixed residential/commercial Walden, Illinois community does not promise any savings when equipped with a HP-ICES, primarily on account of the low cost of natural gas in the Chicago area. A community of this kind may be a candidate for HP-ICES when newly constructed, but it is not viable as a retrofit in such a low gas-cost area.

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 preferred to live in single-family dwellings, or if they did not actually live in them, they aspired to do so. 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 these countries, district heating systems have been extensively used for years, and in a number of European countries, notably Sweden, Finland, and West Germany, district heating is being aggressively pursued as a matter of national policy.

This report 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, the distributed heat pump installations, evaluates technical and economic performance, addresses environmental implications, discusses potential applications throughout the United States, and evaluates the application of the HP-ICES concept to two specific communities.

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.

The authors wish to thank Mr. Jacinto F. Gammino, Executive Director of the Housing Authority of Phillipsburg, New Jersey, and Mr. Christopher Sutherst and Mr. Keith Snidtker of the Ingersoll-Rand Corp., Phillipsburg, New Jersey for their invaluable advice and assistance in the application of the HP-ICES concept to Heckman Terrace Annex.

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 with single family residences represented by "A" blocks, small commercial/industrial buildings represented by "B" blocks and large commercial/industrial/institutional buildings represented by "C" blocks. Motels and multi-family dwellings could be represented by type "A" or "B" buildings. 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 3-3. As shown in Figure 3-1, 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 would also contain a central plant as shown in Figure 3-1. The central plant would contain the necessary pumps to circulate water through the loop piping, and also 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 of 60°F, 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 would be possible.

3.2 HP-ICES IN A REFERENCE COMMUNITY

The community shown in Figure 3-2 is called, for the purposes of 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 13.1. Information pertaining to the reference community is contained in Tables 3-1 and 3-2. Referring to Figure 3-2, the ICES central plant is located in the lower right hand corner of the 857-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

Figure 3-1. HP-ICES Concept

Figure 3-2. Reference Community

Figure 3-3. HP-ICES Branch Piping

Table 3-1. Reference Community Composition

	Quantity	Average Zoned Density	Individual Building Area (ft ²)	Total Building Area (ft ²)	Zoned Land Area (acres)	Gross Land Area (acres)	Population
Single-family houses (2 stories)	1500	4/acre	1600	2,400,000	375.0	501.3	6,000
Townhouses (2 stories)	750	6/acre	1200	900,000	125.0	166.6	2,250
Low-rise apartments (2,3 stories)	750	12/acre	1000	750,000	62.5	83.3	1,750
Elementary School (1 story)	1	20%*		60,000	7.5	10.0	
Secondary School (1 story)	1	15%*		100,000	8.3	11.0	
Office Buildings (1 to 6 stories)		30%*		270,000	7.5	10.0	1,300
Light Manufacturing (1 story)		30%*		320,000	26.6	34.4	2,200
Commercial (1 story)		30%*		300,000	25.0	33.3	1,000
Churches	5		6000	30,000	2.5	3.3	
Recreation Centers	5		6000	30,000	2.5	3.3	
Streets (25% of gross area)						214.1	
TOTAL						856.5	10,000

*Percent of zoned land area 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 (2 story)	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 School (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 Centers	0.3	0.3	1.7	1.2
TOTAL	101.7	100.0	135.4	100.0

cooling loads fed by various distribution mains are shown in rectangular blocks on Figure 3-2. 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 indicated by the information above and to the right of the ICES central plant in Figure 3-2. 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 857-acre community. For costing purposes, the layout of a typical residential area was developed and is shown in Figure 3-3.

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 wasteheat 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.

3.3.2 HP-ICES Central Plant Operation - Heating

(Refer to Figure 3-4 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 HP-ICES loop, several diesel driven air-to-water heat pump systems would be required. The drawing shows one diesel driven air-to-water heat pump system manifolded to the main loop piping. 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 horsepower (hp) diesel engine (Item 3) developing this horsepower at 1200 rpm. The high pressure/high temperature vapor from the centrifugal compressor (Item 1) would discharge into the refrigerant condenser (Item 14), where the latent heat of the condensing refrigerant would raise the loop water temperature from approximately 50°F to 57°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 (e.g., minus 20°F on a 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 to the bottom half of the receiver. Low temperature refrigerant liquid exiting from the receiver (Item 10) would be pumped by the liquid refrigerant pump (Item 11) thru the refrigerant outdoor coil banks (Item 12). Each outdoor coil bank would have a 50,000 cfm fan and motor assembly (Item 13). As outdoor air is blown through the outdoor coil bank (Item 12) the low temperature liquid refrigerant in the coil would be vaporized. The return piping from the outdoor unit would carry heat in the form of refrigerant vapor and some unevaporated liquid to the refrigerant low pressure receiver (Item 10). Within the receiver (Item 10), the refrigerant vapor would collect at the top and the

Figure 3-4. 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 High Pressure 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	

unevaporated liquid would collect at the bottom to be returned to the refrigerant pump. 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).

The compressor prime mover diesel engine (Item 3) would not only drive the refrigerant compressor (Item 1), 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 jacket, and 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 3-4 it can be seen that, down-stream of the discharge of the main water loop pump (Item 15), 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 on the diesel engine waste heat recovery are given in Section 3.8.

A similar branch water piping system is shown in Figure 3-4 to recover the engine waste heat from the 1800 rpm diesel prime mover (Item 17) for 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 3-4). 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.

3.3.4 HP-ICES Central Plant Layout

(Refer to Figure 3-5). This drawing shows a suggested central plant layout for an HP-ICES designed to serve the reference community - if no 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 overheat piping above the equipment.

Shown in Figure 3-5 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 3-5 there is a large air compressor and air receiver station to be used for cranking the diesel engines during start-up cycles.

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 3-5) 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

Figure 3-5. Central Plant Layout

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 the 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 would still have to house the main loop water pumps (P-1 and P-2), the air compressor, and support the cooling tower. In addition, the building would also have to house two 400 horsepower low pressure steam boilers and steam-to-water exchangers to provide for emergency back-up in the event 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. However, two 800 horsepower 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 emergency boiler fuel (probably #4 or #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 3-6, 3-7, and 3-8. 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 3-6) 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 3-6), 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.

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 3-7)

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

is a factory assembled water source heat pump currently available on special order from several manufacturers. It consists of a preassembled and prepiped unit mounted on a structural steel bed plate and includes 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 3-7. 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 3-8) 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) owner will also own the user equipment.

Figure 3-8. 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 many 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.

Most 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 HM-1RCS, made by the Wilgood Corporation, is capable of measuring heat flow both to and from an HP-ICES user (Ref. 3-2).

This meter consists of a turbine flow meter, an electronics package and two indoor/outdoor digital registers. The residential size unit (30 gallons per minute maximum) costs \$310 complete.

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. 3-3). 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 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 within the piping loop and user flow rates would have to be determined and accounted for when determining customer charges.

Commercial and industrial HP-ICES users would be individually metered. Residential users could be charged a flat fee which would vary with the time of year, or could be individually metered. For this study it was assumed that individual metering would not be applied to residential customers.

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 3-4. Table 3-3 identifies the equipment in Figure 3-4. It can be seen in Figure 3-4 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. Because the flow is constant, balancing valves (not shown in Figure 3-4) can be adjusted during system startup to maintain the desired flow distribution.

The diesel engine heat recovery equipment shown in Figure 3-4 was included in this HP-ICES concept to maximize the efficiency with which the central plant uses fuel oil. Since the diesel engines 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.

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. This is accomplished by automatically switching the unit to the cooling mode. Heat removed from the conditioned space is used to melt

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

the frost on the outdoor coil. While the heat pump is in the defrost cycle, electric resistance elements heat the conditioned space. During the defrost cycle the heat pump COP (Coefficient of Performance) is degraded. Many residential heat pumps are defrosted on a time cycle triggered by an ambient temperature sensing thermostat.

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

Central plant heat pumps would have demand defrosting rather than timed defrosting to minimize the number of defrost cycles. Moreover, a modular heat pump plant like the one described here would have 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 would raise the refrigerant evaporating temperature and significantly decrease the frosting rate. Since the central plant would be designed to provide the required loop heat at below-freezing temperatures, the central plant would have capacity in the 32°F to

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

40°F range to permit partial unloading. This operating mode is not provided by the constant speed residential heat pump. Residential units handle partial loads by on-off cycling and this results in unnecessarily low evaporator temperatures and coil frosting.

Defrosting of the HP-ICES diesel driven heat pump outdoor air units (coils) would be initiated when pressure sensors on the outdoor air units detect an increase in the resistance to air flow through the units due to frost accumulation. At that time, the flow of liquid refrigerant to the frosted outdoor units would be interrupted by a solenoid valve (not shown on Figure 3-4) and hot refrigerant gas from the outlet of the compressor would be directed to these units through small refrigerant lines (not shown on Figure 3-4). The hot refrigerant gas condensing in the outdoor air units would melt the accumulated frost. The operating penalty for defrosting is relatively small for residential heat pumps, but is even smaller for large heat pumps of the type that would be used in the HP-ICES central plant, as shown by the following analysis.

The defrost penalty for a residential heat pump was estimated by calculating the annual heating mode energy usage for a 2-1/2 ton heat pump in Philadelphia. Performance data for a General Electric Co. heat pump were used (Ref. 3-4). A defrost penalty of 88 watts was added to the operating energy usage for those hours when the ambient temperature was between 20°F and 40°F (Ref. 3-5). This is the defrost penalty which the Philadelphia Electric Company has found to be representative for its service area. This defrost penalty underestimates energy usage during hours when defrosting actually occurs, but provides a good estimate of the additional energy used for defrosting over the entire heating season. This defrost penalty increases heating season energy usage for a residential heat pump by approximately 2.3%. Since the heat pumps in the HP-ICES central plant have a considerably lower defrost penalty, energy use for defrosting will not affect HP-ICES viability and was therefore not included in the analyses.

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 rise 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 rise 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.

HP-ICES OWNERSHIP
P- PRIVATE M- MUNICIPAL

ENERGY ESCALATION RATES
(ELEC. RATE/OIL RATE)

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 in dense urban centers (energy density greater than 0.63×10^6 Btuh/acre) 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. This is particularly true for new or developing urban centers. If major waste heat sources are found close to urban centers, it will most likely be 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 advantage of HP-ICES relative to the conventional system is significant during the heating season. During the cooling season, both systems use the same amount of resource energy. Consequently HP-ICES is not attractive in regions where little or no heating is required due to the higher initial cost for HP-ICES. Possibly the HP-ICES concept could be modified to function as a cooling-ICES, but this was not investigated.

If the central plant used 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.

HP-ICES has been shown to be a viable alternative to the conventional system for a site having 5000 heating degree-days. It has also been shown that the benefits from HP-ICES occur during the heating season. Thus, for regions having less than 5000 heating degree-days, the range of community characteristics and economic parameters for which HP-ICES would be viable are reduced because, as the number of heating degree-days decreases, the need for space heating lessens. In particular, in regions with a mild heating season, communities with a high average

energy density (e.g., communities consisting mainly of high rise buildings) would be less viable as HP-ICES sites. This is in direct contrast to the fact that a high energy density is a favorable community characteristic in colder climates. A high energy density is a disadvantage in mild climates because building internal heat gains would be such that minimal amounts of heat would be required from the HP-ICES loop. During most of the year the buildings would be rejecting heat to the loop. Consequently the HP-ICES would be primarily a community heat rejection system and would not be economically viable.

The thermal performance of HP-ICES was analyzed in detail using weather data for Philadelphia, PA ($\approx$ 5000 heating degree-days). In order to estimate the quantitative effects of climatic conditions on HP-ICES, a simplified procedure was used to determine the resource energy savings by HP-ICES as a function of heating degree-days.

For the HP-ICES and conventional system users, it was assumed that equipment performance factors did not vary with climate, that heating season energy usage was proportional to heating degree-days, and that cooling season energy usage was proportional to total annual cooling hours. The HP-ICES central plant thermal performance factors for the case of 0% waste heat utilization and 100% waste heat utilization were obtained from Tables 13-8 and 13-10, respectively. Resource energy consumption for HP-ICES and for conventional HVAC systems were then determined for the reference community located in Milwaukee, Atlanta, and Houston in addition to Philadelphia. The heating degree-days and annual cooling hours for these cities are shown in Table 4-2.

The ratio of the resource energy savings by HP-ICES in the reference community to the number of dwelling units in the community is shown in Figure 4-2 as a function of heating degree-days. It can be seen that, as heating degree-days increase, the resource energy saved by HP-ICES increases, and that waste heat utilization has a great impact on these savings. For locations having less than 1000 heating degree-days the resource energy savings by HP-ICES are minimal.

Table 4-2. Climatic Data for Selected Cities

<u>City</u>	<u>Heating Degree-Days*</u>	<u>Annual Cooling Hours*</u>
Milwaukee, WI.	7470	570
Philadelphia, PA.	5144	920
Atlanta, GA.	2990	1320
Houston, TX.	1410	2060

*Obtained from Ref. 4-2.

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 14% to 34% 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 and by recovering diesel engine waste heat, HP-ICES will consume less oil than the conventional alternative. However, the fact that HP-ICES uses oil may limit its application 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,

Figure 4-2. HP-ICES Resource Energy Savings Per Dwelling Unit as a Function of Heating Degree-Days (Based on HP-ICES in the Reference Community)

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. These modifications would increase resource energy consumption, but would result in the conservation of a scarce resource (oil) at the expense of more readily available resources (coal and nuclear energy) and at higher cost. Such systems merit further investigation because they could completely eliminate the consumption of gas and oil for space conditioning.

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 is feasible.

The resource energy consumption by the reference community HP-ICES is 306.1×10^9 Btu/yr. The conventional system resource energy usage is 356.2×10^9 Btu/yr.* The resource energy saved by HP-ICES is therefore 50.1×10^9 Btu/yr and the reference community which has 3000 dwelling units saves 16.7×10^6 Btu of resource energy per year per dwelling unit.

The new construction between 1985 and 2000 will in part replace worn out buildings, as well as add to the total number of buildings in existence. The geographic distribution of this construction will have an effect on the potential of HP-ICES to reduce the nation's use of resource energy during this period. As shown in Figure 4-2, HP-ICES would be more effective in saving resource energy in cold climates. If most of the construction in the near future is in warm climates, the potential for HP-ICES to reduce resource energy consumption will be diminished.

*See Table 5-4.

One projection of the regional distribution of the nation's increase in population between 1985 and 2000 and the total population in 1990 is shown in Table 4-3 (Ref. 4-3). It can be seen that, during the period 1985 to 2000, there will be a migration of people from the north and east to south and west. The cities shown in Table 4-3 were selected based on an estimation of the center of population within each region. The annual heating degree-days for each city are shown in the last column of Table 4-3.

The regional distribution of total U.S. population in 1990 and the regional variations in population increase as shown in Table 4-3 were used to estimate the regional distribution of new construction between 1985 and 2000. It was assumed that half of the new construction would be distributed according to the population distribution in 1990 and half would be distributed according to the variation in migration rates. In the first case, much of the new construction would be for replacement of existing structures whereas, in the second case, the new construction would meet the needs of the newly arrived residents. Applying these assumptions and using the heating degree-days from the last column of Table 4-3, the weighted average heating degree-days for all new construction between 1985 and 2000 would be 4150. Assuming 375,000 dwelling units are to be constructed each year during this period, and using the information presented in Figure 4-2, HP-ICES would save a total of 0.6×10^{15} Btu to 1.3×10^{15} Btu of resource energy depending on whether waste heat utilization was 0% or 100%, respectively. In making this estimate of resource energy savings by HP-ICES it was assumed that, as new dwelling units are constructed during the period 1985-2000, the ratio of commercial, industrial and institutional construction to residential construction would be the same as in the reference community.

Table 4-3. Regional Distribution of U.S. Population and Population Growth

<u>Geographic Region</u>	<u>Percent of Total U.S. Population in 1990</u>	<u>Percent of U.S. Population Increase from 1985 to 2000</u>	<u>Representative City</u>	<u>Heating Degree-Days</u>
New England	5.6	5.0	Boston, MA	5600
Mid Atlantic	15.7	3.7	New York, NY	5000
East North Central	17.8	7.6	Chicago, IL	6200
West North Central	7.4	4.9	Des Moines, IA	6800
South Atlantic	17.6	30.0	Atlanta, GA	2990
East South Central	6.4	6.8	Memphis, TN	3200
West South Central	10.4	14.7	Dallas, TX	2320
Mountain	5.4	10.5	Denver, CO	6200
Pacific	13.7	16.8	San Francisco, CA	3040

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 13. 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 elec- trically driven chiller

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 savings 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 equipment efficiencies used in this analysis for the conventional systems are based on reference 5-4 with allowances for increased performance obtainable from new energy efficient space conditioning 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. (Refer to Section 13.2).

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. The analysis of HP-ICES central plant performance is presented in Section 13.3.5.

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.

The performance factor shown for the central plant in Figure 5-4 (100% waste heat utilization) is less than one because 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 Figure 5-9 with that in Figure 5-3, it can be seen that the performance of the central plant 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 represents a

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

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.

Comparing the central plant performance factors in Figures 5-8 and 5-2, it can be seen that the seasonal performance of the central plant, when no waste heat is utilized, is greater than for the peak heating period. This is because the oil used by the main circulating pump is significantly less than that used by the diesel driven heat pumps and the heat pumps are used for the entire heating season, as compared to the 50% waste heat utilization case when the heat pumps are only used during the coldest part of the heating season.

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 the same 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

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

5-18

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

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.

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:

$$\text{Availability} = (H - H_0) - T_0 (S - S_0) \quad (5-2)$$

where (H) and (S) are the enthalpy and entropy of the energy flow, (T_0) is the temperature of the surroundings, and (S_0) and (H_0) 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:

$$\text{Availability} = \dot{m} C_p [(T - T_0) - T_0 \ln \left(\frac{T}{T_0} \right)] \quad (5-3)$$

where the temperatures are the same as before, ($\dot{m}$) 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:

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

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

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

Noticing that the quantity

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

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. (5-5) 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 values for T_o shown in Figures 5-15 through 5-28 were selected by considering the requirements of the reference community for heat from the HP-ICES loop during the heating season, and the amount of heat rejected to the loop during the cooling season. Based on Philadelphia weather data for 1968, the building heating and cooling load curves, and HP-ICES user equipment performance factors and the building occupancy profiles (refer to Section 13.2.1 and Table 13-1), it was determined that the peak heating load occurred at an ambient temperature of 7°F while the peak cooling load occurred at an ambient temperature of 94°F. Therefore 7°F was used as T_o for peak heating conditions, and 94°F was used as T_o for peak cooling conditions. Ambient temperatures in 10°F increments and their hours of occurrence are shown in the first two lines of Table 13-8. The third line in Table 13-8 gives the net energy required from or rejected to the HP-ICES loop. The values of T_o for the entire heating and cooling seasons were determined by finding the weighted average of the heat required from the loop and rejected to the loop, respectively based on the hours of occurrence. The value of T_o for the entire heating season was determined to be 42°F and the value for the cooling season was determined to be 75°F.

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 have 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.

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

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 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.

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	0.70	0.84
50	0.89	0.66	0.69
100	0.83	0.66	0.68

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	0.52	0.63
50	0.53	0.51	0.51
100	0.31	0.51	0.49

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

HP-ICES Percent Waste Heat Utilization	Ratio of HP-ICES to Conventional System Annual Purchased Energy Requirements		Ratio of HP-ICES to Conventional System Annual Resource Energy Requirements
	<u>Oil</u>	<u>Electricity</u>	
0	2.02	0.72	0.86
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	50.1×10^9 Btu
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 13.

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) and conventional space conditioning systems. The methods 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:

$$\text{Annual Cost (Residential Users)} = \text{Loan Payment} + \text{O\&M}(i) + \text{Energy Costs}(i) + \text{Property Taxes}(i) - [(\text{Interest on Loan}(i) + \text{Property Taxes}(i)) \times \text{Federal Personal Income Tax Rate}]$$
$$\text{Annual Cost (Commercial/Industrial Users)} = [\text{Loan Payment} + \text{O\&M}(i) + \text{Energy Costs}(i) + \text{Property Taxes}(i)] \times (1 - \text{Federal Corporate Income Tax Rate})$$
$$\text{Annual Cost (Schools, Churches, Recreation Centers)} = \text{Loan Payment} + \text{O\&M}(i) + \text{Energy Costs}(i)$$

The three loan payments indicated above would have different interest rates. Specifically, an interest rate of 9.5% was used for the residential mortgage, 11% for the commercial/industrial loan, and a 6.5% rate for the institutional loan (i.e., interest on a bond). It was assumed that all costs were borrowed and that there was no return on equity.

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. Life Cycle Costs of Equipment Owned by Individual Users for Reference Community HP-ICES and for Conventional Systems (Does not include HP-ICES central plant costs)

User	HP-ICES (\$x10 ⁶)	Conventional System (\$x10 ⁶)
Residential	28.6	36.9
Commercial/Industrial	10.6	18.5
Schools, Churches, Recreation Centers	1.3	3.5
Totals	40.5	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 13.

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 Under Private Utility Ownership

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, the privately owned HP-ICES is 1.13 to 1.27 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 under the assumed ownership arrangement. For life cycle costs of HP-ICES under different ownership, see Section 6.5.1.

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

System	Life Cycle Cost (\$x10 ⁶)
HP-ICES - 0% Waste Heat	74.7*
HP-ICES - 50% Waste Heat	70.6*
HP-ICES - 100% Waste Heat	66.3*
Conventional System	58.9

*Privately Owned Utility

The cost of service for HP-ICES and conventional system users is shown in Table 6-5. These costs were calculated by dividing the total life cycle cost for each system (refer to Table 6-4) by 20 (the number of years in the economic analysis), and the total annual space conditioning load (the sum of the annual heating and cooling loads). It can be seen that the conventional system users would have the lowest cost of service and that the cost of service to HP-ICES users decreases as more waste heat is utilized.

Table 6-5. HP-ICES and Conventional System
User Cost of Service

<u>System</u>	<u>Cost of Service (\$/10⁶Btu)</u>
HP-ICES - 0% Waste Heat	17.0*
HP-ICES - 50% Waste Heat	16.0*
HP-ICES - 100% Waste Heat	15.1*
Conventional System	13.4

*Privately Owned Utility

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 used 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 although municipal ownership is the most cost effective, it is not competitive with the conventional system even 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 13. 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.

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

*10,000 population, see Section 13.1

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

(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, as the community energy density increases, the economic aspects of HP-ICES become more favorable. For a community energy density of 0.805,* the minimum waste utilization required for HP-ICES to be competitive is 95%. By extrapolation, it appears that HP-ICES serving a dense urban area (energy density = 0.97)* would require 80% 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. Only at the highest set of escalation rates does HP-ICES become economically competitive with the conventional system.

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

*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

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. The central plant economic analysis is described in Section 13.7.

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. The cost of asbestos-cement pipe is lower than that of steel pipe. However, the cost of labor for putting it in place is not lower when the pipe run contains many turns and branch take-offs. Asbestos-cement pipe is particularly expensive, when branch take-offs must be installed at a later date after the system has been put in place. Therefore, the community system piping was costed for steel pipe. It is conceivable that, in a particular situation, asbestos-cement pipe would be cheaper. Due in part to

the high cost of the loop piping, 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, under certain favorable technical and economic conditions, 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 system costs, 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
- Disposal of the 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.

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 will 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 is retired, the central plant equipment, such as the diesel prime movers, heat pumps, outdoor air coils and auxiliary equipment, will have to be sold or scrapped. The building will either have to be demolished or be converted for other uses after the equipment has been removed. The loop piping would be left in place. Former HP-ICES

users would have to install auxiliary heating equipment and cooling towers or modify/replace the existing equipment.

If the central plant is demolished, short term noise, dust, and traffic problems will result. 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 3-2 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 3-2, 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 3-2 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, a significant amount of manpower may be involved when numerous mobile stations are in operation at the same time.

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 once-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 Atlantic Coast. 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 surface 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. HECKMAN TERRACE ANNEX HP-ICES APPLICATION

10.1 INTRODUCTION

The HP-ICES concept presented in this report was applied to two existing communities. These communities are The Heckman Terrace Annex, a low income residential development in Phillipsburg, New Jersey and Walden, a residential/commercial complex near Chicago, Illinois. The Heckman Terrace Annex HP-ICES application is described in this section of the report and the Walden application is described in Section 11.

10.2 HECKMAN TERRACE ANNEX DESCRIPTION

The Heckman Terrace Annex consists of twenty-four multifamily residential buildings and a central plant (housing the development's central space and domestic water heating systems) on an 18 acre site. A site plan of the development is shown in Figure 10-1.

The Heckman Terrace Annex was constructed in 1952. The residential buildings (numbered 1 through 24 on Figure 10-1) contain 150 dwelling units. These are 2-story frame buildings with a brick veneer on the first story and siding on the second story. Six buildings have an attached bungalow (buildings 16 through 21 on Figure 10-1) and the remaining residential buildings have six dwelling units each. The total floor area for the residential buildings is 147,900 sq. ft. and the average floor area per dwelling unit is 986 sq. ft. The central plant is a one story brick building housing a repair shop and the central heating equipment.

The central heating plant contains two boilers rated at 3.69 million Btuh each which supply the space and domestic hot water heating requirements of the development. There is no space cooling. The boilers can be oil or gas fired, but gas is presently being used. The residential

buildings are heated with hot water radiators. Hot water for these radiators is supplied from the central plant through insulated pipes housed in underground concrete conduits. The routing and sizes of these mains are shown in Figure 10-1. As shown in Figure 10-1, there are two separate space heating hot water loops. One loop serves buildings 1 through 13 and the other loop serves buildings 14 through 24. This is a low pressure central heating system (i.e., maximum supply temperature less than 212°F) and the hot water supply temperature is adjusted automatically by an outdoor thermostat. Each space heating loop has a 15 hp, 450 gpm pump, however, during the milder parts of the heating season, the loops are valved together and only one 450 gpm pump is used.

Domestic hot water is stored in a 1900 gallon tank in the central plant. Hot water from this tank is continually circulated to the residential buildings in pipes occupying the same conduits as the space heating mains. When a resident requires hot water, he draws it directly from these mains.

The Heckman Terrace Annex is situated next to an Ingersoll-Rand industrial facility. A partial site plan of the Ingersoll-Rand complex is shown in Figure 10-2. Low temperature waste heat ($\approx 75^\circ\text{F}$) obtained from Ingersoll-Rand would be used by the Heckman Terrace Annex HP-ICES. It can be seen in Figure 10-2 that waste heat will be obtained at two locations within the Ingersoll-Rand complex. At the foundry division, 90°F water is available continuously at a rate of 70 gpm. In building 12, waste heat (90°F) is available from two large air compressors. One compressor runs continuously and the other runs 80 hours per week. The flow through each compressor is 150 gpm. The heat exchangers shown in Figure 10-2 were sized for a log mean temperature difference (LMTD) of 10°F and equal flows on the hot and cold side. Based on a nominal supply water temperature of 55°F from Heckman Terrace, and the heat exchanger parameters, flow rates, and temperatures mentioned above, the waste heat availability from Ingersoll-Rand would be 2.8 million Btuh for 88 hours per week and 4.6 million Btuh for 80 hours per week. The higher value of waste heat would be available weekdays during the first and second shifts when both air compressors and the foundry division were in operation.

10-4

The Heckman Terrace Annex HP-ICES would only supply space heating. During the summer the system would be deactivated. The peak and annual space heating requirements were derived from past fuel bills. The peak and annual heating loads and fuel requirements are shown in Table 10-1.

Table 10-1. Heckman Terrace Annex Peak and Annual Heating Requirements

	Load (10 ⁶ Btu)	Fuel Required* (10 ⁶ Btu)
Peak Hourly Requirement	7.6 @ -10°F	10.2 @ -10°F
Annual Requirement	14110	18810

*A 75% efficiency was assumed for the central heating system.

A linear relationship between space heating requirements and ambient temperature was developed from fuel bills for the years 1975 through 1978 and local weather data (refer to Section 13.9.1) and is shown below:

$$\text{Heating Load (10}^6 \text{ Btuh)} = 6.6 - 0.10 \text{ TA}$$

where TA is the ambient temperature.

In addition to the boiler fuel required, the space heating system circulating pumps would require 22.4 kW at the peak and 74,835 kWh per year.

Information about Heckman Terrace Annex was obtained from Mr. Jacinto F. Gammino, Executive Director of the Housing Authority of Phillipsburg, New Jersey, and the maintenance staff at Heckman Terrace Annex. Information about Ingersoll-Rand Corp. and the availability of waste heat for use by a Heckman Terrace HP-ICES was supplied by Mr. Christopher D. Sutherst, Manager of Facilities and Mr. Keith E. Snidtker, Energy Manager, at Ingersoll-Rand's Phillipsburg facility.

10.3 HECKMAN TERRACE ANNEX HP-ICES DESCRIPTION

The HP-ICES concept as applied to the Heckman Terrace Annex would use the existing central plant building, boilers, space heating mains, and piping within the residential buildings. The existing 922 hot water radiators would be replaced with console heat pumps. A significant fraction of the natural gas required by the conventional system would be replaced by waste heat from Ingersoll-Rand. The piping required to transfer the waste heat from Ingersoll-Rand to Heckman Terrace Annex is shown in Figures 10-1 and 10-2. The waste heat recovery piping between Ingersoll-Rand's building 12 and the foundry division would be located in an existing pipe tunnel. The remainder of this pipe would be insulated and located underground. The waste heat recovery loop would be interconnected to the existing space heating piping loops as shown in Figure 10-3.

Figure 10-3 shows the modified equipment schematic in the existing central plant building (building 25). Since the existing space heating system circulating pumps are not strong enough to overcome the additional pumping head required to circulate water to and from Ingersoll-Rand, a booster pump (actually a duplex installation) would have to be added as shown in Figure 10-3. The existing boilers are presently connected directly to the space heating water mains. However, in the HP-ICES application, the temperature of the water circulating through these mains would be between 50°F and 90°F as compared to the present system with supply water in the temperature range of 150°F to 200°F. To prevent thermal shock to the boilers due to the lower temperature water in the HP-ICES loop, a heat exchanger and a circulating system including a pump and valve V-1 would have to be installed as shown in Figure 10-3. Valve V-1 would bleed hot water from the boilers into the heat exchanger (labelled HX in Figure 10-3) to maintain the HP-ICES supply water temperature at the desired minimum value of 65°F when the waste heat available was insufficient to accomplish this.

American Air Filter EnerCon console water source heat pumps (model CW06) were chosen for use in this HP-ICES application to minimize the

Figure 10-3. Central Plant Equipment
Heckman Terrace Annex

problems of replacing the existing hot water radiator heating system. These heat pumps are enclosed in cabinets, are free standing, and have individual thermostats. Their heating capacity at 65°F inlet water temperature (7800 Btuh) is essentially equal to the peak output from the individual radiators and their minimum flow requirement is compatible with the flow through the existing radiators (Ref. 10-1).

The HP-ICES system would be used for space heating only. Because Heckman Terrace Annex is a public housing development, and because Phillipsburg summers are mild, cooling is not provided at present and would not be provided by an HP-ICES.

Presently, Heckman Terrace Annex is served by a 4800 volt single phase electric service. Three pole mounted transformers convert the primary service to a 220 volt single phase secondary which goes to each residential building. The central plant has its own transformers and a 440 volt three phase service. The present secondary service to the residential buildings is insufficient to handle the additional load of the console heat pumps. It was determined that the best method of handling this increase in load was to convert the 4800 volt single phase primary to three phase and extend this service throughout the community so that a pole mounted 4800 volt to 220 volt single phase 50 KVA transformer could be installed to serve each residential building.

The existing wiring within the residential buildings is also insufficient to handle the load of the console heat pumps. Rather than change the existing building wiring, new circuits to serve the heat pumps would be installed in weather tight conduits on the outside of the buildings to minimize installation cost. This approach is sometimes used when through-the-wall air conditioners (similar to console heat pumps) are installed in existing buildings.

10.4 THERMAL ANALYSIS

10.4.1 Introduction

First and second law analyses were performed for the conventional and HP-ICES systems. The results are presented in the following discussion.

10.4.2 First Law Analysis

Schematic diagrams of the conventional and HP-ICES systems are shown in Figures 10-4 and 10-5. The results of the first law analysis are shown in Tables 10-2 and 10-3 for the conventional system and HP-ICES. The numbering of the energy flows in Figures 10-4 and 10-5 correspond to the numbering of the rows in Tables 10-2 and 10-3.

From Tables 10-2 and 10-3 it can be seen that over the heating season the HP-ICES would use significantly less central plant fuel (natural gas) than the conventional system (190×10^6 Btu versus 18810×10^6 Btu). While HP-ICES would decrease natural gas requirements, it would require more electricity over the heating season. Specifically, HP-ICES would require 6250×10^6 Btu of electricity over the heating season as compared to 259×10^6 Btu for the conventional system. Since no cooling is required, both the conventional and HP-ICES systems are idle and have no energy requirements during the summer.

In Tables 10-2 and 10-3, system performance is shown for the period of peak heating demand and for a typical operating condition during the heating season. Three peak heating operating conditions are shown for HP-ICES corresponding to maximum waste heat availability from Ingersoll-Rand (first and second shift operation by Ingersoll-Rand on weekdays), minimum waste availability from Ingersoll-Rand under normal conditions (third shift operation on weekdays and on weekends), and an abnormal condition of no waste heat availability. For both the peak heating and typical heating season operating condition HP-ICES would use less central plant fuel (natural gas) than the conventional system but would use more electricity.

Comparing rows 7 and 8 in Table 10-2 and rows 12 and 13 in Table 10-3 it can be seen that HP-ICES would reduce thermal pollution resulting from central plant boiler stack losses as compared to the conventional system. However, HP-ICES would increase thermal pollution from electric power plants due to its increased electricity requirements.

FIGURE 10-4. Conventional System Thermal Analysis Diagram

FIGURE 10-5. HP-ICES Thermal Analysis Diagram

Table 10-2. Conventional System Thermal
Performance - 1st law
(Refer to Figure 10-4)

Energy Flow Identification	HEATING		COOLING	
	Peak @ -10°F 10 ⁶ Btuh	Typical Performance @ 30°F-10 ⁶ Btuh	Annual 10 ⁶ Btuh	Annual
1. Resource energy	10.4	5.1	19586	-
2. Central plant fuel - Nat. Gas	10.1	4.8	18810	-
3. Electric power plant fuel	0.3	0.3	776	-
4. Central plant electricity	0.1	0.1	259	-
5. Heat to conditioned space	7.6	3.6	14108	-
6. Heating load	7.6	3.6	14108	-
7. Central plant stack losses	2.5	1.2	4703	-
8. Electric power plant losses	0.2	0.2	518	-

Table 10-3. HP-ICES Thermal Performance - 1st law
(Refer to Figure 10-5)

Energy Flow Identification	HEATING				COOLING	
	Peak- Weekday @-10°F 10 ⁶ Btu	Peak- Nights/ Weekend 10 ⁶ Btu	Peak- No Waste Heat 10 ⁶ Btu	Typical Performance @-30°F 10 ⁶ Btu	Annual 10 ⁶ Btu	Annual 10 ⁶ Btu
1. Resource energy	13.8	14.6	15.7	4.8	18940	-
2. Electric power plant fuel	9.3	9.3	9.3	4.8	18750	-
3. HP-ICES central plant fuel	4.5	5.3	6.4	0.0	190	-
4. Total elec. to HP-ICES	3.1	3.1	3.1	1.6	6250	-
5. Elec. to HP-ICES central plant	0.1	0.1	0.1	0.1	678	-
6. Elec. to heat pumps	3.0	3.0	3.0	1.5	5572	-
7. Heat to HP-ICES loop from central plant boilers	3.4	4.0	4.8	0.0	143	-
8. Waste heat added to loop	1.4	0.8	0.0	2.1	8048	-
9. Heat extracted from loop by user heat pumps	4.8	4.8	4.8	2.1	8205	-
10. Heat to conditioned space	7.6	7.6	7.6	3.6	14108	-
11. Heating load	7.6	7.6	7.6	3.6	14108	-
12. HP-ICES central plant stack losses	1.1	1.3	1.6	0.0	47	-
13. Electric power plant losses	6.2	6.2	6.2	2.8	12500	-

Comparing resource energy consumption in row 1 of Tables 10-2 and 10-3 it can be seen that HP-ICES would reduce resource energy consumption slightly. Using the methodology and Resource Utilization Factors (RUF's) from Section 12 of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. draft standard 90-75R, the resource utilization by HP-ICES and the conventional system was quantified according to form of resource energy used. The results of this analysis are shown in Table 10-4. It can be seen that the use of HP-ICES would cause a shift from dependence on natural gas to a dependence on other resource energy forms including oil. The total energy value of the resource fossil fuels required by HP-ICES and the conventional system are 7640×10^6 Btu and 20663×10^6 Btu, respectively. Thus, HP-ICES would reduce dependence on hydrocarbon fuels (natural gas and oil) significantly.

Table 10-4. Total Energy Resources Used by HP-ICES and the Conventional System

<u>System</u>	<u>Coal (Tons)</u>	<u>Natural Gas 1000 ft³</u>	<u>Crude Oil (Barrels)</u>	<u>U-235 (Grams)</u>	<u>Hydro- Electric Power (10³kWh)</u>
HP-ICES	366	242	1355	10162	238
Conventional	15	20317	56	421	10

10.4.3 Second Law Analysis

Using the methodology discussed in Section 5.3 of this report, a second law analysis was performed for HP-ICES and the conventional system. The results are shown in Tables 10-5 and 10-6. These tables have nearly the same format as Tables 10-2 and 10-3. The availabilities shown in rows

Table 10-5. Conventional System Thermal
Performance - 2nd law
(Refer to Figure 10-4)

Energy Flow Identification	AVAILABILITY			
	HEATING		COOLING	
	Peak @ -10°F 10 ⁶ Btuh	Typical Performance @ 30°F-10 ⁶ Btuh	Annual 10 ⁶ Btuh	Annual
1. Resource energy	10.4	5.1	19586	-
2. Central plant fuel - Nat. Gas	10.1	4.8	18810	-
3. Electric power plant fuel	0.3	0.3	776	-
4. Central plant electricity	0.1	0.1	259	-
5. Heat to conditioned space	2.3 @200°F	0.8 @170°F	2578 @160°F	-
6. Heating - availability to space	2.3 @200°F	0.8 @170°F	2578 @160°F	-
7. Central plant stack	2.5	1.2	4703	-
8. Electric power plant losses	0.2	0.2	518	-

Table 10-6. HP-ICES Thermal Performance - 2nd law
(Refer to Figure 10-5)

Energy Flow Identification	AVAILABILITY					
	HEATING				COOLING	
	Peak- Weekday @-10°F 10 ⁶ Btu	Peak- Nights/ Weekend 10 ⁶ Btu	Peak- No Waste Heat 10 ⁶ Btu	Typical Performance @ 30°F 10 ⁶ Btu	Annual 10 ⁶ Btu	Annual 10 ⁶ Btu
1. Resource energy	13.8	14.6	15.7	4.8	18940	-
2. Electric power plant fuel	9.3	9.3	9.3	4.8	18750	-
3. HP-ICES central plant fuel	4.5	5.3	6.4	0.0	190	-
4. Total elec. to HP-ICES	3.1	3.1	3.1	1.6	6250	-
5. Elec. to HP-ICES central plant	0.1	0.1	0.1	0.1	678	-
6. Elec. to heat pumps	3.0	3.0	3.0	1.5	5572	-
7. Heat to HP-ICES loop from central plant boilers	0.6 @83°F	0.7 @83°F	0.8 @83°F	0.0	5.7 @65°F	-
8. Waste heat added to loop	0.2 @80°F	0.1 @77°F	0.0	0.1 @65°F	315 @68°F	-
9. Heat extracted from loop by user heat pumps	0.8 @83°F	0.8 @83°F	0.8 @83°F	0.1 @65°F	321 @65°F	-
10. Heat to conditioned space	1.3 @95°F	1.3 @95°F	1.3 @95°F	0.3 @90°F	965 @90°F	-
11. Availability to space	1.3	1.3	1.3	0.3	965	-
12. HP-ICES central plant stack losses	1.1	1.3	1.6	0.0	47	-
13. Electric power plant losses	6.2	6.2	6.2	2.2	12500	-

1 through 4 of Table 10-5 and rows 1 through 6 of Table 10-6 are identical to the quantities of energy used as shown in the corresponding rows of Tables 10-2 and 10-3, because these energy forms (i.e., resource energy, unburned fossil fuel, and electricity) have availabilities essentially equal to their energy content. The central plant stack losses and electric power plant losses (rows 7 and 8 in Table 10-5 and rows 12 and 13 in Table 10-6) are unchanged from the values shown in Tables 10-2 and 10-3 because, although there are availabilities associated with these quantities, they are losses with respect to the community energy systems.

The availability and temperature of the energy delivered by the conventional system to the residential buildings (hot water to hot water radiators) is shown in row 5 of Table 10-5. It can be seen that these values are significantly higher than the corresponding values for HP-ICES as shown in row 10 of Table 10-6. Thus, HP-ICES can perform the function of space heating while supplying less availability to the conditioned space. HP-ICES also uses less resource energy/availability over the entire heating season than the conventional system. As shown in Table 10-6, the electricity supplied to user heat pumps is the single largest use of availability by this HP-ICES. Consequently, the use of more efficient heat pumps is the most likely method of improving HP-ICES performance with respect to the conventional system. American Air Filter Co. console heat pumps were chosen for use in this HP-ICES to facilitate retrofitting the HP-ICES to the existing community. Based on the performance data for these units, the HP-ICES user heat pumps would have a seasonal performance factor (heating load divided by the electric energy input) of 2.53. If suitable heat pumps were available which could achieve a seasonal performance factor of 3.0, user heat pump electricity usage would decrease by 869×10^6 Btu and resource energy consumption would decrease by 14%. This would make HP-ICES more competitive with the conventional system.

10.5 ECONOMIC ANALYSIS

10.5.1 Introduction

Since Heckman Terrace Annex is an existing community, the alternative to installing HP-ICES is to continue to use the existing conventional energy system. If HP-ICES is not installed, the annual costs incurred by the community will be those for energy consumed, operation, and maintenance of the existing system. However, if HP-ICES is installed, the total annual cost will include the cost of capital as well as energy and operation and maintenance costs. If HP-ICES is to be an economical alternative to the conventional system, the savings resulting from decreased energy usage by HP-ICES must offset the HP-ICES installation cost in a reasonable period of time.

10.5.2 Economic Analysis Parameters

The economic analysis was performed using the methodology described in Section 13.7, but some of the economic parameters were changed as shown in Table 10-7. The cost of natural gas in 1980 was derived based on the assumption that the cost of gas would increase by 25% from 1978 to 1980. The escalation rate was chosen assuming that the cost of natural gas would equal the cost of oil in the year 2000 and that oil would cost 75 cents/gallon in 1980 and escalate in cost at an annual rate of 12%.* This resulted in an annual escalation rate of 13.6% (including inflation) for natural gas as shown in Table 10-7. The cost of electricity shown in Table 10-7 corresponds to that for industrial users in 1980 as shown in Appendix A. Heckman Terrace Annex qualifies as an industrial user because electric power is supplied to the complex directly from the utility's distribution lines and all transformers are owned by the community.

The escalation rates for electricity and fossil fuels used in the analysis for Heckman Terrace are higher than those used during the analysis of the reference community (Section 6) because the problems associated with energy availability and supply changed significantly after the

*See footnote p. 10-22.

Table 10-7. Economic Analysis Parameters
for Heckman Terrace

- Type of Ownership - Municipal
- Type of Fuel - Natural gas
- Cost of Fuel in 1980 - \$4.18/10⁶Btu
- Fuel Cost escalation rate - 13.6% per year
- Cost of Electricity in 1980 - \$14.7/10⁶Btu
- Electricity Cost escalation rate - 7% per year
- Inflation Rate - 5% per year
- Market Discount Rate - 7% per year
- Financing - 100% debt financed at 6.5%
- Zero rate of return on equity
- No property taxes
- Analysis performed in current dollars

analysis of the reference community was performed. Specifically, the price of oil and gasoline increased significantly, and President Carter announced plans to decontrol the price of oil. It appeared that fossil fuel cost escalation rates would be much higher in the future than they have been in the past. Also, the cost of fossil fuels would escalate at a much faster rate than the cost of electricity. Presently, natural gas is underpriced with respect to competing forms of energy. For this analysis, it was assumed that this deficiency would be gradually corrected by escalating the cost of natural gas at a higher rate than that of oil so that, by the year 2000, the cost of gas would equal the cost of oil. The annual escalation rates for the costs of electricity and oil were assumed to be 7% and 12%, respectively, for analyzing Heckman Terrace. This compares to the values of 6.5% and 7% used for the analysis of the reference community.

10.5.3 Conventional System Costs

The annual costs associated with the conventional system are for energy and operation and maintenance of the existing heating system. The annual operating and maintenance cost of the conventional system, exclusive of energy costs, is \$4630 (Ref. 10-2).

10.5.4 HP-ICES Costs

A breakdown of the HP-ICES installed cost is shown in Table 10-8. The derivation of these costs is described in Section 13.10. An annual operating and maintenance cost for the distributed heat pumps of \$42.50 per unit (\$39,200 total) was derived based on information obtained from a manufacturer's representative (Ref. 10-7). The maintenance and operating cost for the new equipment in the central plant and the waste heat recovery heat exchangers and piping was estimated to be 2% of the installed cost.

Table 10-8. HP-ICES Installed Cost

● Removal of Existing Radiators	16,600
● Scrap Value of Existing Radiators	- (8,300)
● Installed Cost for 922 Console Heat Pumps	525,500
● 10 Spare Heat Pumps @ \$488 each	4,900
● Installed Cost Waste Heat Recovery Loop Piping, Pumps, and Heat Exchangers	142,300
● Changes to Existing Boilers	19,600
● Rewiring of Community Electrical Distribution System	111,000
● New Wiring added to Existing Buildings	40,000
	<hr/>
Sub-Total	851,600
Contingency (10%)	85,200
	<hr/>
	936,800
Contractor Overhead (10%)	93,700
	<hr/>
	1,032,500
Contractor Profit (10%)	103,100
	<hr/>
	1,133,600

10.5.5 Results

The economics of HP-ICES and the conventional system were analyzed for a period of 20 years. The annual costs associated with each system over this 20-year period are shown in Figure 10-6. It can be seen that the annual cost for the conventional system exceeds that of HP-ICES in 1993.

The life cycle costs of HP-ICES and the conventional system were determined to be $\$3.90 \times 10^6$ and $\$3.19 \times 10^6$ in 1980 dollars, respectively. Thus, HP-ICES is not economically viable in this case.* This is due to the installation cost associated with HP-ICES as compared to the conventional system for which there was no equivalent cost. This HP-ICES application appeared to be economically attractive initially because a significant source of waste heat was located nearby, the distribution pipes already existed and could be used by HP-ICES, and no cooling was required (as shown in Sections 5 and 6, this HP-ICES concept offers no significant advantage over a conventional cooling system). However, the higher initial cost for HP-ICES more than offset the impact of these advantages on HP-ICES economics.

In Section 10.4.3 it was mentioned that higher performance heat pumps would improve HP-ICES thermal performance. If console heat pumps were available which could achieve a seasonal performance factor of 4.0 as compared to the value of 2.53 for the heat pumps considered in this study, the resulting reduction in electricity usage would reduce the HP-ICES life cycle cost to $\$3.17 \times 10^6$ in 1980 dollars. This would make HP-ICES an economically viable option compared to the continued use of the existing conventional system.

*An additional considerable OPEC price increase occurred between the dates of the economic analysis for Heckman Terrace (February/March 1979) and the submission of this report for printing (October 1979). Oil was assumed to cost \$0.75 per gallon in 1980 while the No. 2 heating oil cost in the early fall of 1979 was actually \$0.85 with good prospects of reaching, or even exceeding, \$1.00 during 1980. Under the assumed scenario, natural gas would escalate more rapidly than postulated in Table 10-8, resulting in major changes to the economic analysis. One could, therefore, foresee conditions which would make HP-ICES economically viable for this application.

Figure 10-6. HP-ICES and Conventional System Annual Costs

10.6 INSTITUTIONAL FACTORS ANALYSIS

10.6.1 Introduction

10.6.1.1 Scope

The purpose of this analysis is to explore the major identifiable institutional factors which could affect implementation of the proposed HP-ICES at the Heckman Terrace Annex in Phillipsburg, New Jersey. The investigation has been divided into two parts: Requirements and Constraints. Requirements mean the various fixed standards which must be met before the proposed project can be implemented. These include all applicable laws, construction codes, and similar needs. Constraints refer to factors which influence the feasibility and success of the project, but which are more open in nature. Of course, these distinctions are not absolute so that financing, for example, could be thought of either as a requirement or a constraint.

10.6.1.2 Methodology

The information gathered for this analysis was obtained from telephone and personal interviews of individuals connected with the project, government agencies, and from various references which discuss the institutional factors related to HP-ICES.

10.6.1.3 Results

Most of the institutional considerations examined can be dealt with easily. The greatest barrier to implementation is obtaining the necessary financing.

10.6.2 Requirements

10.6.2.1 Local Requirements

10.6.2.1.1 *Zoning*

Heckman Terrace Annex is an existing low income housing project built

in 1952 under auspices of the U.S. Public Housing Administration (Project No. N.J. --24-1). Since no change of density or new uses are planned, no conflict with zoning requirements is anticipated.

10.6.2.1.2 *Street Crossing*

As shown in Figures 10-1 and 10-2, it will be necessary to carry out the 5-inch waste heat main across Roseberry Avenue in order to connect with the source on the Ingersoll-Rand property. In order to accomplish this, it will be necessary to secure documented permission from the City of Phillipsburg and to coordinate with the Police Department for traffic diversion.

10.6.2.1.3 *Building Code*

The applicable code requirement for Phillipsburg is the BOCA (Building Officials & Code Administrators) Basic Building Code (Ref. 10-5) and Basic Energy Conservation Code (Ref. 10-6). Since this project involves rewiring and installation of a new heat energy system, it appears that only Article 13 (Precautions During Building Operations), Article 15 (Electrical Wiring and Equipment) of the Basic Code apply, together with the Basic Energy Conservation Code. Section 1500.3 states: "Conformity of installations of electric equipment to the applicable standards listed in Appendix B shall be prima facie evidence that such installations are reasonably safe for use in the service intended and in compliance with the provisions of this code." In effect, the National Electrical Code and related codes govern acceptability. A similar situation exists for electrical equipment. Section 1500.4 states: "The materials, fittings, appliances, devices and other equipment listed in publications of inspected electrical equipment of the Underwriters' Laboratories, Inc. (ULI) and other accredited authoritative agencies and testing organizations... shall be accepted as meeting the requirements of this code."

The major electrical work will be to rewire the primary distribution system using 24 transformers, up to ten of which are to be placed

on new poles with the balance on existing poles. The Jersey Central Power and Light Company, which owns the poles, has agreed to this in principle. The Company, however, considers the useful life of the poles to be finished, so that it will be necessary to make an impartial determination of their condition and suitability before proceeding.

Weatherproof conduit will be used on the secondary side and placed around the outside of each of the twenty four buildings at the first floor level, with risers to reach the second floor. It will be necessary to establish that this practice conforms to the applicable electrical codes.

The BOCA Basic Energy Conservation Code places a number of requirements on the rated performance of equipment. Water source heat pumps operating in the heating mode with an inlet water temperature of 60°F must have a COP of at least 2.2. It is also required that "each heating, ventilating and air conditioning system shall be provided with at least one (1) thermostat for the regulation of temperature" (Section 404.2). These conditions are met by the heat pump chosen for this HP-ICES project. Additionally, the power factor of the overall electrical system must be greater than 0.9 or 90 percent (Section 601.1).

10.6.2.1.4 *Fire Prevention and Protection*

These attributes of the project will be the same after installation of heat pumps in a community energy system as it was before. There is no reason to assume that the probability of fire will be affected by the system if all elements meet code requirements.

10.6.2.1.5 *Taxes and Fiscal Impact*

Under the public housing authority, the Heckman Terrace Annex is exempt from property taxes (Ref. 10-2) and therefore the additional value represented by the energy system will not produce additional revenue. It will also not require additional services so that there is no impact.

10.6.2.1.6 *Labor Requirements*

There are no special labor requirements required to construct or operate this system which cannot be met in the Phillipsburg area. The present operating staff is not unionized. Construction labor must be required at prevailing area wage rates or under the Davis-Bacon Act formula depending on the source of funding.

10.6.2.2 State Requirements

10.6.2.2.1 *Public Utility Aspects*

It appears that the system proposed would not be classed as a public utility under the laws of the State of New Jersey, and therefore would not be subject to regulation. Nevertheless, an opinion may be necessary from the Public Utility Commission (PUC) to establish this. The Housing Authority is currently a Gas Line Operator under PUC regulation by virtue of its underground gas system (Ref. 10-2).

10.6.2.2.2 *Department of Environmental Protection*

Since the proposed system involves only energy retrofitting of an existing complex, no New Jersey environmental clearance is required (Ref. 10-3).

10.6.2.2.3 *Taxation*

As a publicly owned property, the project and any improvements to it are not subject to state taxes (Ref. 10-2).

10.6.2.3 National Requirements

10.6.2.3.1 *Department of Housing and Urban Development*

The Department of Housing and Urban Development (HUD) is the successor to the Public Housing Administration which built Heckman Terrace Annex. HUD continues to be involved through subsidization under the "conventional" public housing program (not Section 8). Debt service and

a contribution toward operating expenses are provided. HUD is also a prospective source of funds for HP-ICES. There appear to be no barriers to HP-ICES implementation because of these facts.

10.6.2.3.2 *National Energy Act*

This law encourages individual metering of dwelling units but does not require it. Therefore, either approach can be taken.

10.6.2.3.3 *National Environmental Protection Act*

There appears to be no conflict between the proposed energy system and the environment. In fact, the contribution to air pollution in the immediate area will be reduced as a result of the elimination of combustion boilers. Some of this gain may be offset in other areas as a result of additional generation of electricity. If this project were to be built today with HUD involvement, it would require a "Normal" or possibly "Special" clearance, but not an environmental impact statement. Since it is a retrofit energy system only, it may not require any Federal clearance review, but this was not determined explicitly.

10.6.3 Constraints

10.6.3.1 Financing

Although HP-ICES system has a higher life cycle cost than the conventional system, HP-ICES would use less resource energy. Thus, HP-ICES is attractive from a thermal performance standpoint but not from an economic one. Therefore, obtaining financing could be extremely difficult if not impossible. However, depending on the perceived need for the nation to conserve energy, it may be possible to obtain a sufficient governmental subsidy to justify installing HP-ICES in Heckman Terrace Annex. It was assumed that HP-ICES would be financed by municipal bonds since this would be the least expensive method of acquiring the necessary capital and would therefore result in the lowest life cycle cost, see Section 6 and Figure 4-1, p. 4-3.

10.6.3.2 Consequences of Shutdown

The consequences of system shutdown and the circumstances which might cause this to occur are discussed in Section 7. This should not be a major constraint since equipment critical to system operation is duplicated. Because the user heat pumps are console units, they can be quickly removed and replaced with a spare. Even if waste heat is not available, the existing boilers can handle the load.

10.6.3.3 Ownership

It is envisioned that the HP-ICES and the waste heat recovery system including pipe, pumps and heat exchangers would be owned and maintained by the housing authority in charge of Heckman Terrace Annex. That is, the system would be municipally owned. As shown in Section 6, municipal ownership is economically more favorable than private or cooperative ownership. Since the existing housing development is municipally owned, municipal ownership of the ICES would be logical and would encounter the least institutional barriers.

It is important that the waste heat recovery system function properly. If the system was owned by Ingersoll-Rand, it would be monitored and maintained by the company. If the system was owned by the housing authority, the system's maintenance would be the responsibility of the housing authority's maintenance personnel. Ownership of the waste heat recovery system by the housing authority is preferred because its maintenance staff would be more involved in the day-to-day operations of the HP-ICES and would be more likely to notice malfunctions in the waste heat recovery system. Based on discussions with the Manager of Facilities at Ingersoll-Rand, ownership of the waste heat recovery system by the housing authority does not appear to be a constraint, as long as Ingersoll-Rand is not committed to having to supply waste heat at all times.

11. WALDEN HP-ICES APPLICATION

11.1 INTRODUCTION

The second application like the first involves the retrofitting of HP-ICES to an existing community (completed in 1973). In this case, HP-ICES is applied to the Walden residential/commercial development located near Chicago, Illinois. Information on the layout, composition, and energy requirements of Walden were obtained from Reference 11-1.

11.2 WALDEN DESCRIPTION

A site plan of Walden is shown in Figure 11-1. Buildings 1 through 4 are 3-story apartment buildings with a total floor area of 489,000 ft². There are a total of 410 dwelling units in the four buildings.

The clusters of buildings identified by a 5 and 6 in Figure 11-1 are townhouses. There are 63 townhouses in Walden with a total floor area of 97,870 ft². Building 7 is a 4-story motel with 212 rooms and a total floor area of 90,750 ft². Building 8 is a single story 16,000 ft² commercial building with a bar, restaurant and meeting rooms. Building 9 is a 5-story office building with a total floor area of 75,000 ft². Building 10 does not presently exist. It is the proposed site for the HP-ICES central plant.

The peak and annual heating and cooling loads for the various buildings obtained from Reference 11-1 are shown in Table 11-1. It can be seen that apartments represent the largest single demand for heating and cooling energy and that heating requirements for the total community exceed the cooling requirements.

11.3 HP-ICES DESCRIPTION

Because Walden is an existing community, the present user equipment would have to be replaced with water source heat pumps. Table 11-2

Figure 11-1
 11-2

Table 11-1. Walden Heating and Cooling Loads

Building Type	HEATING		COOLING	
	Peak 10 ⁶ Btuh	Annual 10 ⁶ Btu	Peak 10 ⁶ Btuh	Annual 10 ⁶ Btu
Apartments	11.3	13333	7.4	8155
Townhouses	5.3	6255	2.2	2422
Motel	2.1	2501	2.1	2310
Commercial Building	1.1	793	0.7	827
Offices	3.2	1013	3.1	3417
TOTAL	23.0	23895	15.5	17131

Table 11-2. Conventional System and
HP-ICES User Equipment

Building Type	Conventional System User Equipment	HP-ICES User Equipment
Apartments	Central gas fired water heating system with base-board heaters (390 h.p. boiler) Individual split system electric air conditioners. (410 - 2 ton units)	Water source heat pumps using existing base-board heater piping and the existing air conditioner piping and wiring (410 - 2.7 ton units)
Townhouses	Individual gas furnaces (63 - 85,000 Btuh units) and split system electric air conditioners (63 - 3 ton units)	Water source heat pumps (63 - 7 ton units) connected to existing furnace ducting and air conditioner wiring.
Motel	Individual through-the-wall units containing electric resistance heaters and unitary air conditioners (212 - 1 ton units)	Water source heat pumps (212 - 1 ton console units) with new distribution piping. Reuse of existing wiring.
Commercial Building	Central roof mounted electric air conditioning system (3 - 25 ton units) and gas fired heating system (35 h.p. boiler)	Roof mounted water source heat pumps (4 - 25 ton units) with new distribution piping. Reuse of existing air ducts and wiring.
Offices	Central air handling system with electric duct heaters, baseboard heaters and unit heaters. Central electric air conditioning system (260 ton) with roof mounted cooling tower.	Console heat pumps on building perimeter (122 - 1/2 ton units) with new distribution piping and use of existing wiring. Addition of double bundle condenser and evaporator to existing chiller.

describes the existing space conditioning equipment and the type of equipment that would replace it if HP-ICES was used in Walden. As can be seen in Table 11-2, existing equipment would be used whenever possible.

Equipment sizes as well as types are shown in Table 11-2. The equipment sizes for the conventional equipment were estimated based on the peak heating and cooling loads given in Reference 11-1. The HP-ICES water source heat pumps were sized to meet the larger of the peak heating or cooling loads.

The proposed location for the HP-ICES is shown by building 10 in Figure 11-1. The layout and size of the distribution piping is also shown in Figure 11-1. The HP-ICES loop piping layout is the same as the distribution pattern developed in Reference 11-1 during the study of the feasibility of installing a modular integrated utility system (MIUS) in Walden.

A layout of the HP-ICES central plant is shown in Figure 11-2. This plant is very similar to that described in Section 3 of this report. Since no source of waste heat was identified for Walden, diesel driven air source heat pumps and oil-fired boilers would be used to add heat to the HP-ICES piping loop during the heating season. The central plant would contain two diesel driven heat pumps which could provide the total HP-ICES loop heat requirements at 0°F ambient or above. At ambient temperatures below 0°F, a boiler would supply the additional heating capacity required but not available from the heat pumps. The boiler would also be used if one of the diesel heat pumps was down for repairs. During the summer, heat would be rejected from the HP-ICES loop by means of cooling towers mounted on the roof of the central plant. It can be seen in Figure 11-2 that the diesel driven heat pump outdoor air units are also roof mounted. The cooling towers and outdoor air units would be roof mounted to reduce the land area occupied by the central plant.

If Harmony and Unit Lakes were used as cooling ponds, the peak heat rejection rate would be approximately 15×10^6 Btuh (Ref. 11-1) as compared to the HP-ICES peak heat rejection rate of 20.9×10^6 Btuh.

Figure 11-2. HP-ICES Central Plant Layout

Consequently, cooling towers would be required to supplement the heat rejection from the lakes during the peak cooling period. Rather than have both cooling ponds and towers it was decided to have only cooling towers to minimize the complexity of the heat rejection system and to avoid the necessity of treating the lake water to minimize the possibility of fouling the loop-to-lake water heat exchangers.

11.4 THERMAL ANALYSIS

11.4.1 Introduction

First and second law thermal analyses were performed for the Walden HP-ICES and conventional system.

11.4.2 First Law Analysis

Simplified diagrams of the conventional heating and cooling systems are shown in Figures 11-3 and 11-4, respectively. A simplified diagram of HP-ICES is shown in Figure 11-5. For the first law analysis, heating system efficiencies (η) and heat pump and air conditioner seasonal performance factors (SPF) were assumed to be constant throughout the heating or cooling seasons. The efficiencies and seasonal performance factors shown are assumed values but are believed to be representative for the types of equipment involved. The heat pump seasonal performance factors are based on manufacturer's data as described in Section 13.2.1. The space heating boiler shown in Figure 11-3 is used in the Walden apartments. The motel and offices have electric resistance heat and the commercial building and townhouses have gas-fired forced air heat. The roof top air conditioners shown in Figure 11-4 are used by the Walden commercial building. The apartments, motel, and townhouses have unitary air conditioners and the offices have a central air conditioning system.

Figure 11-3. Conventional Heating System Diagram

Figure 11-4. Conventional Cooling System Diagram

Figure 11-5. HP-ICES Heating/Cooling System Diagram

The results of the First Law analysis are shown in Tables 11-3 through 11-5. The numbering of the rows in these tables correspond to the numbering of the energy flows in the diagrams to which these tables refer.

The ambient temperatures corresponding to the time of the peak heating and cooling loads are shown in Tables 11-3 through 11-5. Actually, the peaks may not occur at exactly these ambient temperatures, however, these temperatures do occur for a few hours per year as indicated by Chicago weather data. For this analysis it was assumed that these temperatures corresponded to the ambient temperatures at the heating and cooling peak demand periods.

Referring to Tables 11-3 and 11-5, it can be seen that at the heating peak HP-ICES would use more resource energy than the conventional system (46.5×10^6 Btuh versus 45.4×10^6 Btuh), but for the entire heating season HP-ICES would use less resource energy (37776×10^6 Btuh versus 44510×10^6 Btuh). Both at the heating peak and for the total heating season, HP-ICES uses less fossil fuel. During the heating season, HP-ICES reduces thermal pollution in the community as compared to the conventional system (refer to row 15 in Table 11-5 and row 9 in Table 11-3). Comparing row 17 in Table 11-5 and row 10 in Table 11-3, it can be seen that HP-ICES will increase thermal pollution by electric power plants.

Cooling season thermal performance for the conventional system and HP-ICES are shown in Tables 11-4 and 11-5, respectively. HP-ICES requires more resource energy at the cooling peak (18.0×10^6 Btuh versus 16.5×10^6 Btuh) and for the entire cooling season (22806×10^6 Btu versus 19323×10^6 Btu) than the conventional system. HP-ICES also uses fossil fuel during the cooling season (1.5×10^6 Btuh at the peak and 4185×10^6 Btu for the season) whereas the conventional system uses no fuel during this period. On-site thermal pollution due to cooling system reject heat will be higher for HP-ICES (26162×10^6 Btu versus 23572×10^6 Btu) than for the conventional system, but thermal pollution resulting from electric power generation will be lower (12414×10^6 Btu versus 12882×10^6 Btu).

Table 11-3. Conventional Heating System
Thermal Performance - 1st law
(Refer to Figure 11-3)

Energy Flow Identification	HEATING	
	Peak 10 ⁶ Btuh	Annual 10 ⁶ Btu
1. Resource energy	45.4	44510
2. Fuel to Electric Power Plant	15.9	10542
3. Nat. gas to user heating equip.	29.5	33968
4. Elec. to user heating equip.	5.3	3514
5. Heat delivered by space htg. boilers	11.3	13333
6. Heat delivered by elec. resistance heaters	5.3	3514
7. Heat delivered by gas furnaces	6.4	7048
8. Heating load	23.0	23895
9. Space heating system losses	49.2	13587
10. Electric power plant losses	10.6	7028

Table 11-4. Conventional Cooling System
Thermal Performance - 1st law
(Refer to Figure 11-4)

Energy Flow Identification	COOLING	
	Peak 100°F 10 ⁶ Btuh	Annual 10 ⁶ Btu
1. Resource energy	16.5	19323
2. Elec. to user cooling equip, .	5.5	6441
3. Elec. to roof top A/C	0.3	306
4. Elec. to unitary A/C	4.0	4957
5. Elec. to central A/C	1.2	1178
6. Cooling by roof top A/C	0.7	827
7. Cooling by unitary A/C	11.7	12887
8. Cooling by central A/C	3.1	3417
9. Cooling load	15.5	17131
10. Heat rejected by community A/C	21.0	23572
11. Electric power plant losses	11.0	12882

Table 11-5. HP-ICES Thermal Performance - 1st law
(Refer to Figure 11-5)

Energy Flow Identification	HEATING		COOLING	
	Peak	Annual	Peak	Annual
	10 ⁶ Btuh -10°F	10 ⁶ Btu	10 ⁶ Btuh 100°F	10 ⁶ Btu
1. Resource energy	46.5	37776	18.0	22806
2. HP-ICES central plant fuel	12.0	11304	1.5	4185
3. Electric power plant fuel	34.5	26472	16.5	18621
4. Total elec. to community	11.5	8824	5.5	6207
5. Elec. to HP-ICES central plant	3.2	229	0.1	238
6. Elec. to user HP-cooling mode	-	-	5.4	5969
7. Elec. to user HP-heating mode	8.3	8595	-	-
8. Heat to HP-ICES loop by central plant	14.7	15300	-	-
9. Heat rejected to HP-ICES loop	-	-	20.9	23100
10. Heat to conditioned space	23.0	23895	-	-
11. Heat removed from conditioned space	-	-	15.5	17131
12. Heating load	23.0	23895	-	-
13. Cooling load	-	-	15.5	17131
14. Heat extracted from ambient air	75.8	6634	-	-
15. Central plant stack losses	3.9	2261	0.3	837
16. Heat rejected by cooling towers	-	-	21.8	26162
17. Electric power plant losses	23.0	17658	11.0	12414

Over the entire year, HP-ICES will reduce resource energy consumption (60582×10^6 Btu versus 63833×10^6 Btu) and on-site thermal pollution (29260×10^6 Btu versus 37159×10^6 Btu). HP-ICES will also reduce the annual use of fossil fuels on-site from 33968×10^6 Btu to $15,489 \times 10^6$ Btu.

The total resource energy impacts for HP-ICES and the conventional system were determined using the methodology and resource utilization factors (RUF's) developed in Section 12 of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. draft standard 90-75R. The total energy resources used by the two systems are shown in Table 11-6. It can be seen that HP-ICES uses more of all sources of resource energy except for natural gas. The energy equivalents of the annual natural gas and oil resource requirements for the alternative systems are 37.1×10^9 Btu for HP-ICES and 50.7×10^9 Btu for the conventional system. Thus, HP-ICES will decrease the overall dependence on hydrocarbon fuels.

Table 11-6. Total Energy Resources Used by HP-ICES and the Conventional System

<u>System</u>	<u>Coal (Tons)</u>	<u>Natural Gas 1000 ft³</u>	<u>Crude Oil (Barrels)</u>	<u>U-235 (Grams)</u>	<u>Hydro- Electric Power (10³kWh)</u>
HP-ICES	6878	7655	5400	44943	150
Conventional	4486	43051	1406	29766	99

11.4.3 Second Law Analysis

A second law analysis was performed for the HP-ICES and conventional systems. The results are shown in Tables 11-7 through 11-9. The numbering of the rows in Tables 11-7 through 11-9 correspond to the numbering of the energy flows in Figures 11-3 through 11-5, respectively.

Table 11-7. Conventional Heating System
Thermal Performance - 2nd law
(Refer to Figure 11-3)

Energy Flow Identification	AVAILABILITY HEATING	
	Peak 10 ⁶ Btuh	Annual 10 ⁶ Btu
	T _o = -10°F	T _o = 43°F
1. Resource energy	45.4	44510
2. Fuel to electric power plant	15.9	10542
3. Nat. gas to user heating equip.	29.5	33968
4. Elec. to user heating equip.	5.3	3514
5. Heat delivered by space htg. boilers	2.9	2246
6. Heat delivered by elec. resistance heaters	1.1	382
7. Heat delivered by gas furnaces	1.3	765
8. Availability supplied to space	5.3	3393
9. Space heating system losses	49.2	13587
10. Electric power plant losses	10.6	7028

Table 11-8. Conventional Cooling System
Thermal Performance - 2nd law
(Refer to Figure 11-4)

Energy Flow Identification	AVAILABILITY COOLING	
	Peak 10 ⁶ Btuh $T_o = 100^\circ\text{F}$	Annual 10 ⁶ Btu $T_o = 76^\circ\text{F}$
1. Resource energy	16.5	19323
2. Elec. to user cooling equip.	5.5	6441
3. Elec. to roof top A/C	0.3	306
4. Elec. to unitary A/C	4.0	4957
5. Elec. to central A/C	1.2	1178
6. Cooling by roof top A/C	0.05	19
7. Cooling by unitary A/C	0.8	296
8. Cooling by central A/C	0.2	79
9. Availability delivered to space	1.1	394
10. Heat rejected by community A/C	21.0	23572
11. Electric power plant losses	11.0	12882

Table 11-9. HP-ICES Thermal Performance - 2nd law
(Refer to Figure 11-5)

Energy Flow Identification	AVAILABILITY			
	HEATING		COOLING	
	Peak 10 ⁶ Btuh	Annual 10 ⁶ Btu	Peak 10 ⁶ Btuh	Annual 10 ⁶ Btu
	T _o = -10°F	T _o = 43°F	T _o = 100°F	T _o = 76°F
1. Resource energy	46.5	37776	18.0	22806
2. HP-ICES central plant fuel	12.0	11304	1.5	4185
3. Electric power plant fuel	34.5	26472	16.5	18621
4. Total elec. to community	11.5	8824	5.5	6207
5. Elec. to HP-ICES central plant	3.2	229	0.1	238
6. Elec. to user HP-cooling mode	-	-	5.4	5969
7. Elec. to user HP-heating mode	8.3	8595	-	-
8. Heat to HP-ICES loop by central plant	1.9	356	-	-
9. Heat rejected to HP-ICES loop	-	-	0.2	790
10. Heat to conditioned space	4.0	1836	-	-
11. Heat removed from conditioned space	-	-	1.1	394
12. Heating-Availability to space	4.0	1836	-	-
13. Cooling-Availability to space	-	-	1.1	394
14. Heat extracted from ambient air	0	0	-	-
15. Central plant stack losses	3.9	2261	0.3	837
16. Heat rejected by cooling towers	-	-	21.8	26162
17. Electric power plant losses	23.0	17648	11.0	12414

In the HP-ICES and the conventional systems, there are three types of energy flows: resource energy (including fossil fuels), 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.

Heating system and HP-ICES stack losses, air conditioning system and cooling tower reject heat, and electric power plant losses are thermal energy flows which have availabilities, but are losses with respect to HP-ICES and the conventional system. Therefore, availabilities were not calculated for these thermal energy flows. The values shown in Tables 11-7 through 11-9 for these losses are equal to their energy values as shown in Tables 11-3 through 11-5.

Using the methodology described in Section 5.3 of this report, availabilities were calculated for the thermal energy flows within the HP-ICES and conventional systems (rows 5 through 8 in Table 11-7, rows 6 through 9 in Table 11-8, and rows 8 through 14 in Table 11-9). Comparing the total availability delivered to the conditioned space during the heating season by HP-ICES and the conventional system (see row 12 in Table 11-9 and row 8 in Table 11-7) it can be seen that the availability supplied by HP-ICES is lower. This is because the temperature of the heat supplied to the space by the HP-ICES user heat pumps is lower than that for the conventional heating systems. HP-ICES also consumes less resource availability during the heating season. Conversely, HP-ICES supplies the same amount of availability to the conditioned space during the cooling season as does the conventional system (refer to row 13 in Table 11-9 and row 9 in Table 11-8) but uses more resource availability.

Improving the thermal performance of HP-ICES could most easily be accomplished by using heat pumps with higher seasonal performance factors and using waste heat instead of diesel driven air source heat pumps. Higher performance heat pumps would decrease electricity use and resource energy consumption, and the use of waste heat would decrease oil use.

11.5 ECONOMIC ANALYSIS

11.5.1 Introduction

Walden is an existing residential/commercial complex. Therefore, while the HP-ICES system would have a large initial cost, there would be no equivalent cost for the conventional system. Consequently, for HP-ICES to be competitive with the conventional system, the operating cost savings resulting from the implementation of HP-ICES would have to offset the HP-ICES installation cost in a reasonable period of time.

11.5.2 Economic Analysis Methodology

The economic analysis for the HP-ICES central plant was performed using the methodology described in Section 13.7. Many of the economic parameters presented in Section 13.7 were used in this analysis. The HP-ICES central plant and loop piping was assumed to be owned by a private profit making utility (the Case I ownership scenario discussed in Section 13.7). The methodology for the economic analyses applied to the HP-ICES and conventional system users is described in Section 6.2. The variations from the methodologies described in Sections 13.7 and 6.2 are an increase in the escalation rate for the cost of oil from 7% to 12% and for electricity from 6.5% to 12%.

The 1980 energy costs used in this analysis are shown in Table 11-10. The electricity costs were derived as described in Appendix A from typical electric bills for Chicago (Ref. A-3). Fuel oil was assumed to cost 75 cents per gallon in 1980. The costs for natural gas shown in Table 11-10 are based on the assumption that the cost of gas in Chicago would increase by 25% between 1978 and 1980. Escalation rates of 16.1% and

Table 11-10. 1980 Energy Costs

	<u>Energy Cost</u> <u>\$/10⁶ Btu</u>
Residential Electricity	11.39
Commercial Electricity	19.17
Industrial Electricity	11.03
Fuel Oil	5.55
Natural Gas - Commercial	2.68
Natural Gas - Residential	3.01

15.5% were derived for commercial gas and residential gas, respectively assuming that the cost of gas would equal the cost of oil by the year 2000 (refer to Section 10.5.2).

11.5.3 Conventional System Costs

The annual costs associated with the conventional system are for energy and operation and maintenance of the existing heating and cooling equipment. The annual operating and maintenance costs for the various conventional system users are shown in Table 11-11.

Table 11-11. Conventional System Operation and Maintenance Costs

<u>User</u>	<u>Operation and Maintenance Cost</u>
Townhouses	13,300
Apartments	63,200
Motel	22,400
Commercial Building	1,900
Offices	4,600
TOTAL	<u>105,400</u>

11.5.4 HP-ICES COSTS

11.5.4.1 HP-ICES Central Plant Costs

The installation costs for the HP-ICES central plant and loop piping are shown in Table 11-12.

Table 11-12. HP-ICES Central Plant
Installed Costs

<u>Component</u>	<u>Installed Cost (\$ x 10⁶)</u>
Building and Land	450,300
Central Plant Equipment	1,159,000
Piping	473,400
TOTAL	2,082,700

11.5.4.2 HP-ICES User Costs

The HP-ICES user costs for the installation of new heating and cooling equipment, including the removal of existing equipment, and the annual operating and maintenance costs for this equipment are shown in Table 11-13.

Table 11-13. HP-ICES User Equipment and Operating
and Maintenance Costs

<u>User</u>	<u>Equipment Installed Cost</u>	<u>Operating and Maintenance Cost</u>
Townhouses	520,500	20,000
Apartments	1,324,000	80,900
Motel	370,100	25,400
Commercial Building	101,200	2,400
Offices	184,700	14,900
TOTAL	2,500,500	143,600

11.6 RESULTS

The economics of HP-ICES and the conventional system were analyzed for a period of 20 years. The annual costs associated with each system over this twenty year period are shown in Figure 11-6. It can be seen that, over the twenty year period, the HP-ICES is always more expensive than the conventional system. As would be expected based on the results shown in Figure 11-6, the life cycle cost for HP-ICES is significantly higher than for the conventional system ($\$14.5 \times 10^6$ versus $\$6.7 \times 10^6$). Therefore it is unlikely that an HP-ICES would be installed in Walden. This is due mainly to the high cost of retrofitting HP-ICES to an existing community. Even a major source of waste heat would not offset the difference in life cycle costs between HP-ICES and the conventional system.

Figure 11-6. HP-ICES and Conventional System Annual Costs

12. 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 limited number of suitable meters. Only one unit was identified which was suitable for residential and small commercial applications. At present, this unit is not applicable to large users. Another unit was identified which could be modified to meet the needs of large HP-ICES users, but it would cost approximately \$2800 per unit. 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 the installation of a piping loop at lower cost than indicated would be of great benefit in advancing the cost effectiveness of the HP-ICES concept.

While water source heat pumps are presently available from a number of manufacturers and have been used in many installations, the HP-ICES concept would be enhanced if the performance of the presently available equipment was improved. The recent entry of additional manufacturers into the water source heat pump market (largely as a result of federal funding for solar assisted heat pumps) will undoubtedly spur development in this direction, and performance improvements can be expected.

13. DESCRIPTION OF ANALYSES

13.1 DESCRIPTION OF REFERENCE COMMUNITY

13.1.1 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.

13.1.2 Land Use Pattern

An overall plan of the reference community is given in Figure 3-2. 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.

13.1.3 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.

13.2 BUILDING THERMAL ANALYSIS

13.2.1 Building Heating and Cooling Load Curves

Figures 13-1 through 13-10 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. 13-1 LOAD CHARACTERISTICS
SINGLE FAMILY RESIDENCE

HEAT FROM "LOOP" = (0.64 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.35 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.106 WATTS/BTU) (HEATING LOAD)
 = (0.102 WATTS/BTU) (COOLING LOAD)

FIG. 13-2 LOAD CHARACTERISTICS
TOWNHOUSES

HEAT FROM "LOOP" = (0.54 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.35 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.106 WATTS/BTU) (HEATING LOAD)
 = (0.102 WATTS/BTU) (COOLING LOAD)

FIG. 13-3 LOAD CHARACTERISTICS
APARTMENTS

HEAT FROM "LOOP" = (0.64 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.35 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.106 WATTS/BTU) (HEATING LOAD)
 = (0.102 WATTS/BTU) (COOLING LOAD)

FIG. 13-4 LOAD CHARACTERISTICS
ELEMENTARY SCHOOL

HEAT FROM "LOOP" = (0.80 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.25 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.065 WATTS/BTU) (HEATING LOAD)
 = (0.068 WATTS/BTU) (COOLING LOAD)

FIG. 13-5 LOAD CHARACTERISTICS
SECONDARY SCHOOL

HEAT FROM "LOOP" = (0.80 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.25 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.065 WATTS/BTU) (HEATING LOAD)
 = (0.068 WATTS/BTU) (COOLING LOAD)

FIG. 13-6 LOAD CHARACTERISTICS
OFFICE BUILDING

HEAT FROM "LOOP" = (0.80 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.25 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.065 WATTS/BTU) (HEATING LOAD)
 = (0.068 WATTS/BTU) (COOLING LOAD)

FIG. 13-7 LOAD CHARACTERISTICS
LIGHT MANUFACTURING

HEAT FROM "LOOP" = (0.80 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.25 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.065 WATTS/BTU) (HEATING LOAD)
 = (0.068 WATTS/BTU) (COOLING LOAD)

FIG. 13-8 LOAD CHARACTERISTICS
COMMERCIAL

HEAT FROM "LOOP" = (0.80 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.25 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.065 WATTS/BTU) (HEATING LOAD)
 = (0.068 WATTS/BTU) (COOLING LOAD)

FIG. 13-9 LOAD CHARACTERISTICS
CHURCHES

HEAT FROM "LOOP" = (0.80 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.25 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.065 WATTS/BTU) (HEATING LOAD)
 = (0.068 WATTS/BTU) (COOLING LOAD)

FIG. 13-10 LOAD CHARACTERISTICS
RECREATIONAL CENTERS

HEAT FROM "LOOP" = (0.80 FACTOR) (HEATING LOAD)
 HEAT TO "LOOP" = (1.25 FACTOR) (COOLING LOAD)
 KWH (OWNER) = (0.065 WATTS/BTU) (HEATING LOAD)
 = (0.068 WATTS/BTU) (COOLING LOAD)

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 13-1 through 13-10 are based on Werden Associates' experience in the design of this type of equipment.

The information at the bottom of Figures 13-1 through 13-10 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.

13.2.2 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 13-1 through 13-10, hourly Philadelphia dry bulb temperatures for 1968, and the building occupancy profiles in Table 13-1. 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 13-2. Note that for other than single family residences or townhouses, the heating loads for buildings in the conventional

Table 13-1. 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 (refer to Section 13.2.1).

13.2.3 HP-ICES and Conventional System User Annual Energy Requirements

Using the heating and cooling loads from Table 13-2 and the equipment performance factors from Figures 13-1 through 13-10, the annual energy requirements of HP-ICES users were calculated and are shown in Table 13-3.

The conventional systems used in this study are shown in Table 13-4. 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 13-2. 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	38345	14800	5152	106600	53300	14800	6167
Townhouses	20140	7245	2881	1003	20140	10070	2881	1200
Apartments	22170	7975	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 13-3. 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	51.7	70.7	-
Apartments, Offices and Commercial Buildings	14.7	31.3	26.6
Light Manufacturing	3.2	3.2	7.4
Schools, Churches, and Recreation Centers	0.8	0.3	5.3
TOTALS	70.4	105.6	39.2

Table 13-4. 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 13-3 were calculated using the heating and cooling loads in Table 13-2 and the equipment performance factors in Table 13-4.

13.3 HP-ICES CENTRAL PLANT THERMAL PERFORMANCE

13.3.1 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 13-5.

Table 13-5. 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%

13.3.2 Centrifugal Compressor Characteristics

The estimated performance of a compressor with a two-stage impeller as manufactured by York is shown in Table 13-6. 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 13-6. 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 bypass)

Table 13-6 tabulates the performance of the compressor as to evaporator temperature, reduced speed increments, evaporator tons, and brake horsepower (all at 65°F condensing temperature). If the speed of a centrifugal compressor is reduced to less than 75% of its full load speed, the compressor will begin to surge. For this machine, the minimum speed is 4392 RPM. Consequently at evaporator temperatures of 20°F and above, hot gas must be bypassed from the compressor discharge to suction to reduce capacity.

13.3.3 Diesel Driven Heat Pump Characteristics

The estimated heat pump characteristics are shown in Table 13-7 as a function of evaporator temperature. The evaporator capacity (Line 1) and the prime mover brake horsepower (Line 2) are taken from Table 13-6. 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 13-5. The fuel input to the diesel is shown in Line 9.

Table 13-7. 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

13.3.4 Outdoor Air Unit Performance Characteristics

Figure 13-11 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 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).

13.3.5 HP-ICES Central Plant Performance

13.3.5.1 0% Waste Heat Utilization

Table 13-8 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. A given heat pump compressor can be operated at various evaporator temperatures regardless of outdoor temperature. As the evaporator temperature is varied, the compressor capacity and horsepower requirements will vary along with the number of outdoor air units and their fan power requirements. For each ambient temperature, there is an optimum evaporator temperature which will minimize the total power requirements by the heat pump compressors and the outdoor air unit fans. The extent to which this minimum power requirement can be approached is determined by the maximum capacity of the heat pumps with respect to the load, and the need to keep at least one heat pump on standby.

Referring to Table 13-8, 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

Figure 13-11. Estimated Performance for a Typical Outdoor Air Unit with a 10 HP Fan and 100 sq. ft. Face Area

Table 13-8. Heat Pump - ICES Central Plant Performance* (No Waste Heat Available)

Line	Outdoor Temp., °F	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
1.	Annual Hours-Ref. Community	0	134	528	973	1290	1363	1679	1387	1132	261
2.	Energy Req'd. from HHP-ICES Plant**	74.0	53.6	43.5	33.6	22.6	12.2	2.6	-5.15	-28.27	-68.5
3.	Energy added to HHP-ICES Loop by circulating pump	0	2.2								
4.	Fuel Req'd. by circulating pump	0	2.7								
5.	Net Energy Req'd. by HHP-ICES Loop (2-3)	0	51.4	41.3	31.4	20.4	10.0	0.4	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°	10.0/ +10°	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
8.	Energy extracted from ambient air per Heat Pump Evaporator		9.6/ -20°	8.16/ -5°	7.2/ +5°	7.2/ +5°	6.72/ +10°	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
10.	Energy extracted from ambient air per Fan Unit	0	.94/ -20°	.755/ -5°	.755/ +5°	1.28/ +5°	1.22/ +10°	0	0	0	0
11.	No. of Fans Req'd. (9:10)	0	32	33	26	10	6	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
13.	Total Fuel Req'd by Heat Pump	0	27.16	20.36	14.52	9.4	4.71	0	0	0	0
14.	Total Fan Energy	0	.81	.84	.66	.25	.15	0	.38	.51	.64
15.	Total Energy Req'd by Heat Pumps including Fan	0	27.97	21.2	15.18	9.65	4.86	0	0	0	0
16.	Central Plant Performance Factor (5:15)	0	1.84	1.95	2.07	2.11	2.06	-	-	-	-

* Energy units are Btu/h x 10⁶

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

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 13-7. The total energy extracted from ambient is given in Line 9. The information in Line 10 is obtained from Figure 13-11. 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 Line 9 of Table 13-7. 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.

13.3.5.2 50% Waste Heat Utilization

The central plant performance for the case of 50% waste heat utilization is shown in Table 13-9. The description of Table 13-8 for the case of 0% waste heat utilization also applies to Table 13-9. Comparing Line 3 in Table 13-8 and 13-9, it can be seen that the values in Line 3 of Table 13-9 are less than those in Table 13-8 by a factor of 50% due to the availability of waste heat.

13.3.5.3 100% Waste Heat Utilization

The performance of the central plant with 100% waste heat utilization is shown in Table 13-10. 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.

Table 13-9. Heat Pump - ICES Central Plant Performance* (50% Waste Heat Available)

Line	Outdoor Temp, °F	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
1.	Annual Hours-Ref. Community	0	134	528	973	1296	1363	1679	1387	1132	261
2.	Energy Req'd. from HP-ICES Plant**		26.8	16.7	6.8	0	0	0	-5.15	-28.27	-68.5
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
6.	Energy Avail. from each diesel heat pump/evaporator temp.		16.65/ -20°	13.56/ -5°	10.5/ +10	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
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
9.	Total energy extracted from ambient air (7x8)		14.2	8.73	2.96	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
11.	No. of Fan Units Req'd(9:10)		15	12	5	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
13.	Total Fuel Req'd by Heat Pump		13.0	7.19	2.1	0	0	0	0	0	0
14.	Total Fan Energy		.38	.31	.13	0	0	0	.38	.51	.64
15.	Total Energy Req'd by Heat Pumps including Fans		13.38	7.5	2.23	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 13-10. Heat Pump - ICES Central Plant Performance* (100% Waste Heat Available)

Line Outdoor Temp, °F	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
1. Annual Hours - Ref. Community	0	134	528	973	1296	1363	1679	1387	1132	261
2. Energy Req'd. from HP-ICES Plant**	0	0	0	0	0	0	0	-5.15	-28.27	-68.
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
4. Total Fan Energy	0	0	0	0	0	0	0	.38	.51	.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

* Energy units are Btuh x 10⁶

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

13.3.5.4 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 13-8, 13-9, 13-10, 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.

13.4 HP-ICES PIPING LOOP HEAT LOSS

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

$$Q = \frac{K_g 2 \pi L}{\cosh^{-1} (2Z/D)} (T_f - T_a) \quad (\text{Ref. 13-6})$$

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.

13.5 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 13-1 and 13-2, 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. The equipment costs are shown in Table 13-11. 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 13-11.

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 shown in Table 13-11. Based on heating and cooling system costs presented in Reference 13-3, 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. That is, 25% of the conventional system costs for nonresidential buildings, as shown in Table 13-11, was assumed to be for an oil fired heating system. 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 13-4, 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 13-5. 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 condenser add-on were applied to the conventional system costs to derive the HP-ICES user equipment costs shown in Table 13-11.

It can be seen in Table 13-11 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 13-1 and 13-2. 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 13-3, 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 13-11. 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

13.6 HP-ICES CENTRAL PLANT AND LOOP PIPING COST ESTIMATE

13.6.1 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 13-12 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 13-12. Total ICES System Cost Estimate

	<u>Percent Waste Heat Utilization</u>		
	<u>0%</u>	<u>50%</u>	<u>100%</u>
Loop Piping	6935254	6935254	6935254
Central Utility Plant	3499673	3049206	1358544
Sub Total	10434927	9984460	8293794
Engineering Design (8%)	834794	198756	663503
Estimated Total Project Cost	11,269,721	10,783,216	8,951,297

13.6.2 Loop Piping Cost Estimate

The cost of a typical branch main was estimated based on the layout in Figure 3-3. 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 3-2 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 13-13.

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.

13.6.3 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 included as backup to the waste heat source. Central plant cost estimates are shown in Tables 13-14 through 13-16. 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).

Table 13-13. Piping Costs

<u>Quantity</u>	<u>Units</u>	<u>Application</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
<u>Typical Branch Mains*</u>					
500	ft	4" Sched. 40	12.35	6175	
750	ft	3" Sched. 40	9.10	6825	
750	ft	2" Sched. 40	5.82	4365	
1000	ft	Trenching	.83	830	
1000	ft	Back fill & Tamping	1.32	1320	
		(per 26 single family dwellings)			
				19515	
		Aver. Price/dwelling	780.00		
		Aver. Price/Acre	3120.00		
1500		Dwelling Branches	780.00	1,170,000	1,170,000
750		Townhouses @ 6/acre	520.00	390,000	390,000
750		Apartments @ 12/acre	260.00	195,000	195,000
1		Elem. School			
1000	ft	4" Sched. 40	12.35	12350	
500	ft	Trenching	.83	415	
500	ft	Backfill & Tamping	1.32	660	
				13425	13425
1		Sec. School			
1000	ft	6" Sched. 40	22.25	22250	
500	ft	Trenching	.83	415	
500	ft	Backfill & Tamping	1.32	660	
				23325	23325
		Office Bldgs (270,000 ft ²)			
		(No branches-fed from main)			
		Light Manufacturing (320,000 ft ²)			
1200	ft	8" Sched. 40	29.45	35340	
600	ft	Trenching	.83	498	
600	ft	Backfill & Tamping	1.32	792	
				36630	36630
		Commercial (300,000 ft ²)			-
		(No branches-fed from main)			
		Churches (30,000 ft ²)			-
		(No branches-fed from main)			
		Recreation (30,000 ft ²)			-
		(No branches-fed from main)			
		SUB-TOTAL			1,828,380

Table 13-13. Piping Costs (Cont.d)

<u>Quantity</u>	<u>Units</u>	<u>Application</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		Brought Forward			1,828,380
		<u>Distribution Mains*</u>			
13,400	ft	18" Sched. 40	96.64	1294976	
11,600	ft	16" Sched. 40	72.98	846568	
4,400	ft	14" Sched. 40	63.00	277200	
11,400	ft	12" Sched. 40	48.00	547200	
6,600	ft	10" Sched. 40	42.40	279840	
23,700	ft	Trenching	1.66	39342	
23,700	ft	Backfill & Tamping	2.64	62568	
				<u>3,347,694</u>	3,347,694
		<u>Utility Plant Mains*</u>			
680	ft.	24" Sched. 40	145.76	99116	
160	ft.	18" Sched. 40	96.64	15462	
8		18" OS&Y Valves	950.00	7600	
4		24" Butterfly Valves	2220.00	8800	
2		24" Basket Strainers (Box Type)	5000.00	10000	
				<u>130,978</u>	130,978
		Total Loop Piping Cost to Contractor			<u>5,307,052</u>
		Contingency 10%			<u>530,705</u>
					<u>5,837,757</u>
		Est. Contractor Overhead 10%			<u>583,775</u>
					<u>6,421,532</u>
		Est. Contractor Profit 8%			<u>513,722</u>
					<u><u>6,935,254</u></u>

*all Mains are Black Steel

Table 13-14. Central Utility Plant Cost Estimate
(0% Waste Heat Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
1		Building 7500 ft ²		375000	375000
2.1	acre	Land	75000	157500	157500
4		HP systems (based on York #238 compr., complete w/gear, condenser, L.P. receiver & liquid pump sets)	155000	620000	
4		Diesel Prime Movers (based on Caterpillar D399-SCAC-85s, compl. w/Flywheel coupling & heat exchangers)	115000	460000	
4		Exhaust Silencers	2000	8000	
4		Exhaust Stacks	1200	4800	
		Rigging, Field Erection of 4 HP Systems	15000	60000	
		Rigging, Field Erection & alignment of 4 Diesel Prime Movers	10000	40000	
4		Foundations	3500	14000	
2		Main H ₂ O Loop Pumps (based on Aurora 14x16x 18 Model 411)	14000	28000	
2		Pump Diesel Prime Movers (based on Caterpillar D379-SCAC-85s, compl. w/heat exchangers)	70000	140000	
2		Pump-Engine Foundations	2500	5000	
1		Air Compressor, Air Rec'r (for cranking diesels)	6000	6000	
1		Air Compressor Foundation	1000	1000	
		SUB-TOTAL		1,386,800	532,500

Table 13-14. Central Utility Plant Cost Estimate (Cont'd)
(0% Waste Heat Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		(Brought Forward)		1,386,800	532,500
48	100 ft ²	Outdoor Air Coil Banks (Based on Trane Co.)	4700	225600	
48		Outdoor Air Fans & Motor Drives (based on Western 72"-VAX 73 #N72620)	1147	55056	
48		Outdoor Air Shroud- Transitions (based on Peabody & Wind)	1000	48000	
48		Coil Bank Footings	500	24000	
4		Sets of liquid recircula- ting refrigerant mains			
320	ft	6" Sched. 40	22.45	7184	
320	ft	4" Sched. 40	12.35	3952	
320	ft	3" Sched. 40	9.10	2912	
960	ft	2" Sched. 40	5.82	5587	
96		2" globe valves, w/strs.	210.00	20160	
68400	lbs	Refrigerant charge	.72	49248	
		Insulation (shells, pipe, pumps)		40000	
1		Central control console w/microprocessor, et al.		50000	
2	20,000 gal.	Diesel fuel tanks	6925	13850	
2		Tank excavation, pads, piping, etc.	8000	16000	
		SUB-TOTAL		1,948,349	1,948,349
		SUB-TOTAL			2,480,849

Table 13-14. Central Utility Plant Cost Estimate (Cont'd)
(0% Waste Heat Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		(Brought Forward)			2,480,849
		<u>Electric Wiring</u>			
3	60 hp	Outdoor Air Fans-480 HP		24000	
		Cooling Tower Fans	2400	7200	
		Control Wiring		500	
1	100 hp	Air Compressor		3000	
		Central Console		6000	
		Misc. Pumps & Controls		6000	
				<u>46,700</u>	46,700
1		Cooling Tower-erected (Based on Marley Segall) averaged w/B.A.C. 3 cell			150,500
		SUB-TOTAL			<u>2,678,049</u>
		Contingency* 10%			<u>267,804</u>
					<u>2,945,853</u>
		Est. Contractor Overh'd 10%			<u>294,585</u>
					<u>3,240,438</u>
		Est. Contractor Profit 8%			<u>259,235</u>
					<u><u>3,499,673</u></u>

*Known items not in estimate include silencers and stacks for H₂O pump diesels.

Table 13-15. Central Utility Plant Cost Estimate
(50% Industrial Waste Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
1		Building 6380 ft ²		319000	319000
1.8	acre	Land	75000	135000	135000
3		HP Systems (based on York #238 compr.coupling w/gear, condenser L.P. receiver & liquid pump sets)	155000	465000	
3		Diesel Prime Movers (based on Caterpillar D399-SCAC-85s, comp. w/Flywheel coupling & heat exchangers)	115000	345000	
3		Exhaust Silencers	2000	6000	
3		Exhaust Stacks	1200	3600	
		Rigging & Field Erection of HP Systems	15000	45000	
		Rigging, erection & alignment of Diesel Engines	10000	30000	
3		Foundations	3500	10500	
2		Main Loop H ₂ O Pumps (based on Aurora 14x16x18s)	14000	28000	
2		Pump Diesel Pump Prime Movers (based on Caterpillar D379-SCAC-85s compl. w/heat exchangers)	70000	140000	
2		Pump-Engine Foundations	2500	5000	
1		Air Compressor, Air Receiver (for cranking diesels)	6000	6000	
1		Air Compressor Foundation	1000	1000	
		SUB-TOTAL		1,088,100	454,000

Table 13-15. Central Utility Plant Cost Estimate (Cont'd)
(50% Industrial Waste Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		(Brought Forward)		1,088,100	454,000
36	100 ft ²	Outdoor Air Coil Banks	4700	169200	
36		Outdoor Air Fan & Motor Drives (based on Western 72"-VAX 73 #N72620	1147	41292	
36		Outdoor Air Shroud- Transitions (based on Peabody & Wind)	1000	36000	
36		Coil Bank Footings	500	18000	
3		Sets of liquid recircu- lating refrigerant mains			
240	ft	6" Sched. 40	22.45	5388	
240	ft	4" Sched. 40	12.35	2964	
240	ft	3" Sched. 40	9.10	2184	
720	ft	2" Sched. 40	5.82	41 0	
72		2" globe valves w/strs.	2.10	15120	
51300	lbs	Refrigerant Charge	.72	36936	
		Insulation		30000	
		Central control console w/microprocessor, et al.		50000	
2	15,000 gal	Diesel fuel tanks	5420	10840	
		Tank excavation, pads, piping, etc.	7000	14000	
		SUB-TOTAL		1,524,214	1,524,214
		SUB-TOTAL			1,978,214

Table 13-15. Central Utility Plant Cost Estimate (Cont'd)
(50% Industrial Waste Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		(Brought Forward)			1,978,214
		<u>Electric Wiring</u>			
1	360 hp	Outdoor Air Fans	18000	18000	
3	60 hp	Cooling Tower Fans	2400	7200	
		Cooling Tower Control Wiring		500	
1	100 hp	Air Compressor	3000	3000	
		Central Console		6000	
		Misc. Pumps & Controls		6000	
		SUB-TOTAL		40,700	40,700
1		Cooling Tower-erected (based on Aver. Marley & B.A.C.)			150,500
2	400 hp	Low pressure boilers	28000	56000	
2		Sets Boiler Foundations, frt, rigging, erection, stack, et al.	21000	42000	
1	20,000 gal	Boiler fuel oil tank	6925	6925	
1		Tank excavation, pads, piping, etc.	8000	8000	
		SUB-TOTAL		112,925	112,925
2		Steam-to-Loop H ₂ O heat exchangers	11500	23,000	
2		Sets steam piping & specialties	8000	16,000	
2		Sets insulation	6000	12,000	
		SUB-TOTAL		51,000	51,000
		SUB-TOTAL			2,333,339
		Contingency 10%			233,333
					2,566,672
		Est. Contractor Overh'd 10%			256,667
					2,823,339
		Est. Contractor Profit 8%			225,867
					3,049,206

Table 13-16. Central Utility Plant Cost Estimate
(100% Industrial Waste Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
1		Building 6000 ft ²		300000	300000
.75	acre	Land	75000	56250	56250
2		Main H ₂ O Loop Pumps (based on Aurora 14x16x18s)	14000	28000	
2		Pump Diesel Prime Movers (based on Caterpillar D-379-SCAC-85s compl. w/heat exchanger	70000	140000	
2		Pump Engine Foundations	2500	5000	
2		Exhaust Silencers	2000	4000	
2		Exhaust Stacks	1200	2400	
1		Air Compressor for Diesel Cranking w/air receiver, etc.	5000	5000	
1		Air Compressor Foundation	1000	1000	
1	15000 gal	Diesel fuel tank		5420	
		Tank excavation, pads, piping, etc.	7000	7000	
		SUB-TOTAL		197,820	197,820
1		Cooling Tower erected (based on aver. of Marley & B.A.C.)		150,500	150,500
2	800 hp	Low Pressure Boilers (based on Superior)	45000	90,000	
2		Sets, boiler foundations, frt, rigging, erection, stacks, et al.	33750	67,500	
1	20000 gal	Boiler fuel tank	6925	6,925	
1		Tank excavation, pads, piping, etc.	8000	8,000	
		SUB-TOTAL		172,425	
		SUB-TOTAL			704,570

Table 13-16. Central Utility Plant Cost Estimate (Cont'd)
(100% Industrial Waste Available)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		(Brought forward)		172,425	704,570
		Steam Plant		172,425	172,425
2		Steam-to-loop heat exchangers	15500	31000	
2		Sets of steam piping & specialties	12000	24000	
2		Sets of insulation	8000	16000	
				<u>71,000</u>	71,000
		Electrical Wiring			
3	60 hp	Cooling Tower Fans	2400	7200	
1	100 hp	Air Compressor	3000	3000	
		Cooling Tower Control Wiring		500	
		Central console		6000	
		Misc. controls		6000	
		SUB-TOTAL		22,700	22,700
1		Central Control Console w/microprocessor, etc.		50,000	50,000
		SUB-TOTAL			1,020,695
		Contingency 10%			102,069
					<u>1,122,764</u>
		Estimated Contractor Overh'd 10%			112,276
					<u>1,235,040</u>
		Estimated Contractor Profit 10%			123,504
					<u>1,358,544</u>

13.7 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.13-45)
- 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%.
- Overhead is 10% of the annual variable costs.

The methodology applied in the economic analysis is largely based on the DOE publication of Reference 13-3.

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:

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

*See Appendix B for an explanation of how this rate was selected.

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, and overhead to be 10% of the total annual variable 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 13-17 and 13-18 as a function of waste heat utilization, type of ownership, and community energy density. The first line of Table 13-17 was taken from Table 6-3, lines 2 and 3 were obtained by calculating the life cycle cost factors for Cases II and III above and comparing them to Case I. 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 13-17. 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 13-18. HP-ICES Central Plant and Loop Piping Life Cycle Cost as a Function of Waste Heat Utilization and Community Energy Density (\$ x 10⁶)

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

13.8 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.

13.8.1 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 3-2 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 reduce its energy requirements by half.

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 3-2) 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 3-3. Branch main costs per dwelling unit for single family residences, townhouses and apartments are shown in

Table 13-13. 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.

13.8.2 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 13-12.

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 13-18. It can be seen that HP-ICES economic feasibility is quite sensitive to community energy density.

13.9 HECKMAN TERRACE ANNEX HP-ICES APPLICATION

13.9.1 Building Heating Load

Heckman Terrace Annex uses natural gas for the existing central plant boiler fuel, and cooking. Gas usage is metered at a single point.

Gas bills for the years 1975 through 1978 and weather data from Allentown, PA were used to develop the following relationship between ambient temperature and boiler fuel usage:

$$F = 8.8 - 0.13 TA$$

where F is the boiler fuel required in 10^6 Btuh and TA is the ambient temperature in °F. Assuming a boiler efficiency of 75%, the heating load as a function of temperature is given by:

$$\text{Heating Load } (10^6 \text{ Btuh}) = 6.6 - 0.10 TA$$

13.9.2 User Heat Pump Performance

American Air Filter EnerCon console heat pumps (model CW06) were chosen to replace the existing hot water radiators. The performance data for these units was obtained from American Air Filter bulletin ENER-1-117-Dec.-01.

13.9.3 Central Plant Performance

The HP-ICES central plant performance is shown in Table 13-19. The values in line 4 were derived from American Air Filter (AAF) heat pump performance data. AAF model CW06 console units were chosen for this project because their minimum required flow rate is equal to that through the existing radiators. While these units can operate at loop temperatures below 50°F, a nominal loop temperature of 65°F was selected to improve the heat pumps' seasonal performance factor. However, at ambient temperatures of 0°F and below, the heat pumps have insufficient capacity to meet the load. Therefore the loop temperature must be boosted during these periods; to 67°F at 0°F ambient and 83°F at -10°F ambient.

Plate heat exchanger costs are shown in Table 9-1. These prices are for units with a log mean temperature difference of 10°F. The values in line 5 of Table 13-19 were calculated based on the return temperature from the user heat pumps and the quantity of 90°F heat available from Ingersoll-Rand. For example, very little waste heat can be used

Table 13-19. Central Plant Performance

1. Outdoor Temp. °F	-10°	0°	10°	20°	30°	40°	50°	60°	Total
2. Hrs. Incidence/Year	1	8	85	378	1350	1559	1360	1564	
3. Heat Req'd. by Bldgs. x 10 ⁶ Btu/hr	7.6	6.6	5.6	4.6	3.6	2.6	1.6	0.5	
4. Heat Req'd. in Loop to Produce Line 3.	4.8	4.0	3.4	2.8	2.2	1.6	1.0	0.3	
5. a Waste Heat Av'ble (50% of the time)	1.4	4.2	4.2	3.9	3.7	3.4	3.2	2.9	
b Waste Heat Av'ble (50% of the time)	0.8	2.5	2.5	2.3	2.2	2.0	1.9	1.7	
6. a Deficiency (4-5a)	3.4	-	-	-	-	-	-	-	
b Deficiency (4-5b)	4.0	1.5	0.9	0.5	-	-	-	-	
7. a 50% Line 2 x 6a	1.7	-	-	-	-	-	-	-	
b 50% Line 2 x 6b	2.0	6.0	38.3	94.5	-	-	-	-	
8. Total (7a + 7b)	3.7	6.0	38.3	94.5	-	-	-	-	142.5
9. Fuel Use(Based on 75% Efficiency)x 10 ⁶ Btu									190.0

when the ambient temperature is -10°F because the loop supply temperature must be elevated to 83°F in order that the user heat pumps can meet the load.

13.9.4 Equipment Costs

13.9.4.1 Introduction

The costs presented in Section 13.9.4 represent the cost of material and labor. For the economic analyses, these costs were increased by a factor of 1.33 to account for 10% overhead, 10% profit and 10% contingency.

13.9.4.2 Heat Pump Installation

The American Air Filter console heat pumps model CW06 cost 488 each including a hose kit and valves (Ref. 13-7). A combined total installation time of 4-1/2 manhours per unit at a rate of \$17.88/hour was assumed. The total installed cost per unit was \$570.

13.9.4.3 Waste Heat Recovery Loop Costs

The installed costs for the waste heat recovery loop piping, pumps and heat exchanger (see Figures 10-1, 10-2, and 10-3) are shown in Table 13-20. It can be seen that the major cost is for piping.

Table 13-20. Waste Heat Recovery Loop Costs

<u>Item</u>		
Foundry Heat Exchanger	4,200	
Air Compressor Heat Exchangers (2)	<u>18,000</u>	22,200
2-1/2" pipe (1000', insulated, underground)	13,300	
5" pipe (2000', uninsulated pipe in tunnel)	22,100	
5" pipe (2900', insulated, underground)	75,000	
Heat exchanger isolation valves	<u>2,300</u>	112,700
Waste Heat loop booster pumps (duplex installation)	7,400	<u>7,400</u>
		142,300

13.9.4.4 Central Plant Modification Costs

The costs for the modifications to the existing central plant (see Figure 10-3) are shown in Table 13-21.

Table 13-21. Central Plant Modification Costs

<u>Item</u>	<u>Cost</u>
Reorifice boilers	1,000
Boiler circulating pump and valve V-1	800
Heat exchangers	12,800
Misc. pipe and controls	<u>5,000</u>
TOTAL	19,600

13.9.4.5 Heckman Terrace Annex Rewiring Cost

The cost of rewiring Heckman Terrace Annex was estimated by Werden Associates. The rewiring costs are shown in Table 13-22.

Table 13-22. Heckman Terrace Annex Rewiring Costs

<u>Item</u>	<u>Unit Cost</u>	<u>Total</u>
50 KVA Transformer (24)	1200	28,800
New pole insulators and cross arms (50)	78	3,900
New poles (10)	350	3,500
New single phase 4800 volt primary on existing poles (2880 ft)	7.80	22,500
Addition of third phase to existing 4800 volt primary (3000 ft)	2.60	7,800
Primary fuses (2 per transformer)	140	3,400
New secondary wiring from poles to buildings (720 ft.)	7.50	5,400
New supports for secondary on poles (24)	140	3,400
New secondary wiring on building exterior (10,600 ft.)	3.70	39,300
Cabinet containing heat pump circuit breakers mounted on building exterior (24)	680	16,400
Individual heat pump junction boxes (922)	18	<u>16,600</u>
TOTAL		150,900

13.10 WALDEN HP-ICES APPLICATION

13.10.1 Building Thermal Loads

Building heating and cooling loads as a function of ambient temperature were developed using the peak and annual heating and cooling load data for the Walden buildings as presented in Reference 11-1. The loads presented in Reference 11-1 were averaged over eight years. Therefore, it was assumed that these loads were representative of those that would be expected based on average weather data for Chicago.

The number of hours of occurrence corresponding to 10°F increments of ambient temperature, averaged over ten years, were obtained for Chicago. On the average, there are 15 hours at -10°F (-15°F to -5°F) and 29 hours at 100°F (95°F to 105°F). The peak heating and cooling loads were assumed to occur at these temperatures (i.e., -10°F and 100°F).

Using the peak and annual heating and cooling loads from Reference 11-1, and the hours of occurrence at 10°F increments of ambient temperature, linear relationships between ambient temperature and building heat gain and loss were developed. These equations are shown in Table 13-23

Table 13-23. Building Heating and Cooling Load Equations

Townhouse	$H = 45.25 - 0.91 TA$ $C = 33.69 + 0.56 TA$
Apartments	$H = 19.29 - 0.39 TA$ $C = -22.68 + 0.38 TA$
Motel	$H = 19.5 - 0.39 TA$ $C = -34.62 + 0.58 TA$
Commercial Building	$H = 47.28 - 1.43 TA$ $C = -70.29 + 1.17 TA$
Offices	$H = 32.33 - 1.08 TA$ $C = -61.97 + 1.03 TA$

where H and C are the heat loss and heat gain per square foot of floor area, respectively, and TA is the ambient temperature (°F).

13.10.2 Central Plant Heat Pump Characteristics

The HP-ICES central plant diesel heat pump characteristics are shown in Figure 13-12 and Table 13-24. The performance of these units and their diesel prime movers and outdoor air units is similar to the equipment performance characteristics discussed in Sections 13.3.1 through 13.3.4. The only major difference is that the compressor characteristics shown in Table 13-6 are for a 2-stage compressor whereas a 3-stage unit would be required in Walden. The added stage increases the compressor capacity at low ambient temperatures.

13.10.3 HP-ICES Central Plant Performance

The HP-ICES central plant performance as a function of ambient temperature is shown in Table 13-25. Diesel engine performance is based on the information in Section 13.3.1. Heat pump performance is based on the information in Figure 13-12 and Table 13-24. Outdoor air unit performance is discussed in Section 13.3.4.

13.10.4 HP-ICES Central Plant Cost Estimate

The central plant and loop piping cost estimates performed by Werden Associates are shown in Table 13-26 (central plant cost), and Table 13-27 (loop piping cost).

13.10.5 HP-ICES User Equipment Costs

The HP-ICES user equipment costs described below include the cost of labor and material in 1980, but not contractor overhead, profit or contingency fee. Breakdowns of the cost to install heat pumps in the various buildings in Walden are shown in Tables 13-28 through 13-32.

The cost to remove small capacity cooling equipment (townhouses, apartments and the motel) was based on a labor requirement of 1.5 man-hours per unit to disconnect and remove at a rate of \$12.00/hour. The

Figure 13-12

CENTRIFUGAL COMPRESSOR RATINGS

(BASED ON YORK 3 STAGE, R-12)

- WITH INTERSTAGE COOLING -

@ 65° F. CONDENSING TEMP.

MODEL No.	MULTIPLIER	CFM
326 A	1.00	2562
326 B	0.68	1740
325 A	0.457	1170

R.W. 3-13-79

Table 13-24. Estimated Diesel Driven Heat Pump Characteristics

Line	Evaporator Temp. °F	-30°	-25°	-20°	-15°	-10°	-5°	0°
1	Capacity (tons) Model 326-A	272	256	240	222	204	188	172
2	Brake Horsepower	503	472	441	383	324	272	220
3	Energy Input at Evaporator - x 10 ⁶ Btu	3.26	3.07	2.88	2.66	2.45	2.26	2.06
4	Heat of Compression - x 10 ⁶ Btu	1.28	1.20	1.12	0.97	0.82	0.69	0.56
5	Heat Pump Engine Jacket Recovery x 10 ⁶ Btu	0.88	0.82	0.77	0.66	0.56	0.47	0.38
6	Heat Pump Engine Exhaust Recovery x 10 ⁶ Btu	0.71	0.67	0.62	0.54	0.46	0.38	0.31
7	Heat Pump Engine After Cooler Recovery x 10 ⁶ Btu	0.22	0.20	0.19	0.17	0.14	0.12	0.08
8	Total Heat Output (3+4+5+6+7) x 10 ⁶ Btu	6.35	5.96	5.58	5.00	4.43	3.92	3.39
9	Fuel Input x 10 ⁶ Btu	3.84	3.60	3.36	2.91	2.46	2.07	1.68

Table 13-25. Heat Pump-ICES Central Plant Performance

Line	Outdoor Temp. °F	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
1	Annual Hours	15	85	203	532	1375	1394	1116	1250	1534	919	308	29
2	Energy Req'd from ICES Loop	15.5	12.7	9.8	7.0	4.2	2.0	-	-	(5.2)	(10.3)	(15.5)	(20.6)
3	Added to Loop by Circ. Pump & Engine	1.2	1.2	1.2	1.2	1.2	1.2	-	-	(1.2)	(1.2)	(1.2)	(1.2)
4	Fuel Req'd by Circ. Pump & Engine	1.5	1.5	1.5	1.5	1.5	1.5	-	-	1.5	1.5	1.5	1.5
5	Net Energy Req'd by ICES-H.P. (2 minus 3) Boiler Supplement Net from H.P.	14.3 4.5 9.8	11.5 - 11.5	8.6 - 8.6	5.8 - 5.8	3.0 - 3.0	0.8 - 0.8			(6.4)	(11.5)	(16.7)	(21.8)
6	Energy Available from Each Diesel Heat Pump @ Evap. Temp.	6.35 @-30°	5.96 @-25°	4.43 @-10°	3.39 @ 0°	3.39 @ 0°	3.39 @ 0°						
7	No. of HP's Req'd. (5÷6)	1.55	1.93	1.95	1.71	0.89	0.24						
8	Energy Extracted from Outdoor Air per Heat Pump	3.26	3.07	2.45	2.06	2.06	2.06						
9	Total Energy From Air (7x8)	5.05	5.93	4.77	3.52	1.83	0.50						
10	Energy From Air Per Fan Unit	0.63	0.80	0.63	0.63	0.90	1.20						
11	No. Fan Units Req'd. (9÷10)	8	7.4	7.6	5.6	2.03	0.42						
12	Fuel Req'd Per Heat Pump	3.84	3.60	2.46	1.68	1.68	1.68						
13	Total Fuel Req'd by Heat Pumps	6.00	6.96	4.80	2.88	1.50	0.40						
14	Total Fan Energy	0.21	0.19	0.19	0.14	0.05	0.02						
15	Total Energy Req'd by HP's & Fans	6.21	7.15	4.99	3.02	1.55	0.42						
16	Central Plant Performance Factor		1.61	1.73	1.92	1.93	1.90						
	HP	1.575											
	Boiler Fuel @ 75%	6.0											
	HP + Boiler Energy	12.21											
	Overall Perf. Factor (HP +Boiler)	1.17											

Table 13-26. Walden-Central Plant Cost Estimate

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
1		Building 6272 ft ²		313600	313600
.5	acre	Land	75000	37500	37500
2		Heat Pump Systems (based on York #326A compressor complete with gear, condenser, L.P. receiver & liquid pump sets)	140000	280000	
2		Diesel Prime Movers (based on Caterpillar #D379 complete with flywheel coupling & heat exchanger)	90000	180000	
2		Exhaust Silencers	2000	4000	
2		Exhaust Stacks	1200	2400	
		Necessary rigging, field erection of 2 HP systems	15000	30000	
		Necessary rigging, field erection & alignment of 2 Diesels	10000	20000	
2		Foundations	3500	7000	
2		Main H ₂ O loop pumps	12000	24000	
2		Pump Diesel Engines based on Caterpillar #3306	20000	40000	
2		Pump-Engine Foundations	2500	5000	
1		Air Compressor/Air Receiver (for cranking)	5000	5000	
1		Air Compressor Foundation	1000	1000	
		SUB-TOTAL		598,400	351,100

Table 13-26. Walden-Central Plant Cost Estimate (Cont'd)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		(Brought Forward)		598,400	351,100
8	100 ft ²	Outdoor Air Coil Banks (based on Trane Co.)	4700	37600	
8		Outdoor Air Fans & Motor Drives (based on Western 72"-VAX 73 #N72620)	1147	9176	
8		Outdoor Air Coil Shrouds- Transitions (based on Peabody-Wind)	1000	8000	
8		Outdoor Air Supports	500	4000	
	2	Sets of Refrigerant Mains			
240	ft	4"-L.P. Vapor	12.35	2970	
240	ft	3"-L.P. Liquid	9.10	2170	
240	ft	2"-H.P. Gas	5.82	1400	
240	ft	1-1/2" H.P. Liquid	4.50	1100	
16		2" Globe valves w/strs.	210	3360	
8		1-1/2" Check Valves	180	1440	
32		1-1/2" Solenoid Valves	200	6400	
30,000	lbs	Necessary Refrigerant Charge	.72	21600	
		Necessary Insulation (shells, pipe, pumps)		25000	
1		Central Control Console		40000	
1	20,000 gal	Diesel Fuel Tank	6950	6950	
1		Tank Excavation & Pad etc.	8000	8000	
		SUB-TOTAL		777,566	777,566
		SUB-TOTAL			1,128,666

Table 13-26. Walden-Central Plant Cost Estimate (Cont'd)

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
		(Brought Forward)			1,128,466
		<u>Electrical Wiring</u>			
		Outside Air Fans 80 hp		4000	
		Cooling Tower Fans 50 hp		2000	
		Cooling Tower Cont.Wiring		500	
		Air Compressor 50 hp		2000	
		Central Console		5000	
		Misc. Pumps & Control		3000	
		Boiler & Control		1500	
		SUB-TOTAL		18,000	18,000
1		Cooling Tower (based on Marley-2 cell)		47,000	47,000
1		Boiler (based on Kewanee H35500 w/heat exchanger)		53,000	53,000
1		Boiler Stack		3,000	3,000
		Boiler erection, fuel lines, etc.		5,000	5,000
		SUB-TOTAL		1,254,466	
		Contingency 10%		125,446	
				<u>1,379,912</u>	
		Estimated Contractor Over'd 10%		137,991	
				<u>1,517,903</u>	
		Estimated Contractor Profit 6%		91,074	
		TOTAL		<u><u>1,608,977</u></u>	

Table 13-27. Loop Piping Cost Estimate

<u>Quantity</u>	<u>Units</u>	<u>Item</u>	<u>Unit Cost</u>	<u>Component Cost</u>	<u>Project Cost</u>
<u>Distribution Mains</u>					
1900	ft	12" Sched. 40	48.00		91,200
1400	ft	8" Sched. 40	29.45		41,230
2700	ft	6" Sched. 40	22.25		60,075
2400	ft	4" Sched. 40	12.35		29,640
4200	ft	Trenching & Backfill	4.30		18,060
<u>Utility Plant Mains</u>					
680	ft	12" Sched. 40	48.00		32,640
160	ft	8" Sched. 40	29.45		4,712
6		8" O.S.&Y. Valves	1505.00		9,030
4		12" O.S.&Y. Valves	3065.00		12,180
2		12" Strainers	4000.00		8,000
<u>Branch Mains</u>					
63		Town House Branch Lines	780.00		48,940
SUB-TOTAL					355,707
Contengency - 10%					35,570
					<u>391,277</u>
Contractor Overhead - 10%					39,127
					<u>430,404</u>
Contractor Profit - 10%					43,040
TOTAL					<u><u>473,444</u></u>

Table 13-28. Townhouse HP-ICES Equipment
Installed Costs (63 Buildings)

<u>Item</u>	<u>Cost</u>
Removal of existing air conditioners	1,270
Scrap value of existing equipment	- 10,300
Modifications to existing ducting	15,800
Heat pump installed cost	384,300
TOTAL	391,900

Table 13-29. Apartment Building HP-ICES Equipment
Installed Costs (4 Buildings)

<u>Item</u>	<u>Cost</u>
Removal of existing split system air conditioners	8,500
Scrap value of existing air conditioners	- 49,200
Modifications to existing baseboard hot water piping and air conditioner ducting	82,000
Heat pump installed cost	884,800
Heat exchangers, piping, pumps and controls required to connect the existing boilers to the distribution piping	65,400
TOTAL	991,500

Table 13-30. Motel HP-ICES Equipment
Installed Costs

<u>Item</u>	<u>Cost</u>
Removal of existing through-the-wall air conditioners	4,300
Scrap value of existing units	- 9,500
New distribution piping	67,200
Heat pump installed cost	216,100
TOTAL	278,100

Table 13-31. Commercial Building HP-ICES
Installed Costs

<u>Item</u>	<u>Cost</u>
Removal of existing roof top units	1,000
Scrap value of existing units	- 4,900
New distribution piping	5,700
Heat pump installed cost	68,500
	<hr/>
TOTAL	70,300

Table 13-32. Office Building HP-ICES
Equipment Installed Costs

<u>Item</u>	<u>Cost</u>
Removal of existing electric heating units	17,400
Central air conditioning system modifications	23,300
New distribution piping	26,000
Heat pump installed cost	72,000
	<hr/>
TOTAL	138,700

cost to remove roof top units (commercial building) was derived assuming it would take one manhour per ton of capacity to disconnect and remove the units at \$12.00/hour. The cost of removal for electric duct heaters, baseboard heaters and unit heaters (offices) was assumed to be equal to the installation cost as presented in Reference 11-1.

The equipment costs for small packaged and split system air conditioners were obtained from reference 13-1. Although the costs in reference 13-1 are actually for air source heat pumps, it was assumed that the cost of equal size cooling equipment would be nearly the same. The cost of roof top air conditioners (commercial building) was obtained from reference 13-8. A scrap value equal to the 10% of the cost (i.e., replacement cost in 1980) of removed air conditioning equipment was used.

Since this equipment would only be 8 years old at time of removal, it might be of value to firms in the business of parts rebuilding and reconditioning.

The installed cost for small capacity heat pumps (townhouses, apartments, and the motel) were obtained from reference 13-2. The cost of console water source heat pumps (offices) and roof top water source heat pumps (commercial building) were obtained from reference 13-7.

The installation of suitable HP-ICES user equipment in the motel, commercial building and offices would require the installation of new distribution piping within these buildings. The cost of this piping is shown in Tables 13-30 through 13-32. The piping material and labor costs were obtained from reference 13-8. The labor costs were increased by 25% to account for the added complications of installing the pipe in existing buildings. In addition, a cost of \$20 per penetration was included for holes in floors and partitions. The existing boilers in the apartment buildings would be retained to provide added backup to the HP-ICES central plant. The cost of the equipment required to connect these boilers to the HP-ICES loop is shown in Table 13-29.

The existing central air conditioning system in the office building would be converted to a Type B heat pump (see Section 3.4.2) by the addition of a double bundle chiller and condenser. This system would serve the building core and the air distribution system to the building perimeter. Perimeter conduction heat gains and losses would be offset by console heat pumps installed on the exterior walls (i.e., under windows). The added cost for the double bundle condenser at \$3.33/1000 Btuh of heating capacity (Reference 13-5) and the double bundle chiller at \$4.17/1000 Btuh of cooling capacity (Ref. 13-5) are shown in Table 13-32.

13.10.6 HP-ICES and Conventional System User Operating and Maintenance Costs

The total operating and maintenance costs by category of user for the conventional system and HP-ICES are shown in Tables 11-11 and 11-13, respectively. The conventional system and HP-ICES user equipment is identified in Table 11-2.

The equipment sizes shown in Table 11-2 were used to determine operating and maintenance costs (exclusive of energy costs). Operating and maintenance (O&M) costs in 1976 dollars for unitary water-to-air heat pumps were obtained from Reference 13-2. Similar information for unitary air conditioners was obtained from Reference 13-9. In Reference 3-3, O&M costs in 1976 dollars of \$14/boiler horsepower and \$14/ton of cooling capacity are given for boilers and central air conditioning systems, respectively. In each case, the O&M costs in 1976 dollars were escalated to 1980 costs at a rate of 6% per year. The annual O&M costs for the conventional system residential gas furnaces were assumed to be \$50 per furnace. This information on O&M costs was used to derive the costs shown in Tables 11-11 and 11-13.

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APPENDIX A
FUEL PRICES

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

<u>Fuel</u>	<u>Fuel Price (\$/10⁶Btu)</u>		
	<u>1980</u>	<u>1990</u>	<u>2000</u>
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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APPENDIX B

EFFECTIVE CORPORATE INCOME TAX
RATE FOR PRIVATELY OWNED UTILITY

The corporate tax reforms which were enacted in 1978 and which became effective as of 1979 specify that the U.S. corporate income tax rates will be as follows:

17% on first \$25,000 of corporate profits
20% on next \$25,000
30% on next \$25,000
40% on next \$25,000
46% on all profits in excess of \$100,000

If the HP-ICES central plant is privately owned, and achieves the 9% return on investment assumed for the case of private ownership in this economic analysis, the annual profits would be approximately \$1 million on which taxes of \$440,000 would be due at an effective rate of 44%.

Because of various provisions favoring investment, and permitting rapid write-offs, the effective tax rates paid by utilities are significantly lower than the tax rate structure shown previously would indicate (Ref. B-1). In view of this fact, a corporate income tax rate of 34% was assumed for the privately owned ICES utility. This rate is approximately half-way between the minimum tax rate and the theoretical tax rate that would apply to a utility having corporate profits of \$1 million.

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Distribution

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