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Heat-Pump-Centered Integrated Community Energy Systems

System Development

Rocket Research Company Final Report

ENERGY AND ENVIRONMENTAL
SYSTEMS DIVISION

ARGONNE NATIONAL LABORATORY

OPERATED FOR THE U. S. DEPARTMENT OF ENERGY
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HEAT-PUMP-CENTERED
INTEGRATED COMMUNITY ENERGY SYSTEMS
System Development
Rocket Research Company Final Report*

by

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November 1979

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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 Urban Waste and Municipal Systems Branch, Community Systems Division, Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Applications, 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 Rocket Research Company.

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INTRODUCTION

The utilization of industrial waste heat for community applications offers a large, near-term energy conservation potential. Industrial waste heat quantities exceeding 10×10^{15} Btu's are available; however, the delivered energy must 1) have sufficient quality (temperature level) for the application, and 2) be economically competitive with conventional sources.

Since a large quantity of the available industrial waste energy occurs at low temperatures in various outfall streams, heat pumps may be used to elevate this energy to a useful state. Two system concepts that allow for use of this energy have been identified:

1. The heat pumping function may be performed at or near the heat source (central heat pump system) or
2. The heat pumping function may be performed at the site of the energy demand (distributed heat pump system).

Waste energy is captured at the plant and transported to the demand sites as sensible energy in liquid water, through a distribution network of buried insulated pipes. Heat pumps are used to increase the temperature of this energy for convective heating systems. The heating of potable water, and provision for space cooling as well as heating, are two additional services that may be provided from the basic system.

During this effort, various tradeoffs associated with the location of the heat pump device(s) were investigated. For example, large centralized heat pumps, close coupled to the energy source, benefit from economics of scale when compared to a series of smaller devices distributed at the user sites. For conditions where simultaneous heating and cooling is to be supplied, distributed systems will be more advantageous since the centralized heat pump requires more complex piping systems. Weather patterns will also greatly effect the eventual choice.

An additional series of configurations is introduced when considering incorporation of energy storage at some location in the system. Advantages are available for storage at the source location (both before and after the heat pumping process), and at the use site. Advantages of these various locations accrue from the ability to utilize a greater fraction of the energy source, the ability to deliver higher peak energy demand from a given heat pump capacity, and the ability to deliver higher peak demand from a given piping system, respectively. Local climatological characteristics may dictate which storage location provides the best overall capability at the lowest cost, and whether the additional expense of the storage system is justified by increased capability.

Mechanical, Rankine heat pump equipment is chosen as a baseline, since such equipment is entirely proven technology.

It is recognized that many options for ownership of the system are possible. The distribution system will undoubtedly be owned and operated as a private or public utility. Either the expansion of the charter of an existing utility or the formation of a new utility is possible. Heat exchangers, central heat pumps, storage facilities, etc., will be located near the source of waste energy upon the property of or adjacent to the industrial concern producing the waste energy. None, some, or all of this equipment can be owned by the industrial concern with the utility owning the rest. At the users site, equipment to produce the desired conditioned air may be owned by the user, or leased from the utility, or partly owned partly leased.

The many combinations of these ownership options will each have unique economic properties. In order that a fair comparison be made between the two heat pump system concepts, both are analyzed based upon the assumption that a new publically owned utility will be formed which will own and maintain all equipment associated with the system as well as bear any retrofit costs incurred during system installation. If it can be shown that the expenses incurred by such a utility are less than the expenses which would be incurred by the subscribers in operating their conventional systems, then the economic viability is considered proven. This difference in expense will be shared in some manner between payment to the industrial concern for its energy (and the inescapable disturbance to its operations, albiet small), savings to the subscribers (some incentive to subscribe must be provided), and perhaps profit to the utility with the exact sharing arrangement specific to each individual system.

1.0 SYSTEM DESCRIPTION

Two HP-ICES concepts are under investigation. Both systems utilize high COP heat pumps arranged to draw low temperature energy out of industrial waste heat streams and deliver high temperature energy to supply the residential and commercial space heating demand and potable water heating demand. Energy is transmitted to the demand locations as sensible energy in liquid water. Each system is composed of five subsystems:

1. Energy Source and Associated Hardware
2. Heat Pump(s)
3. Distribution subsystem
4. Topping Boiler/Storage Subsystem
5. User Equipment

The primary difference between the two systems is found in the location of the heat pump(s). If the heat pumping function is performed before the distribution function, then the system is termed a central heat pump approach. If the heat pumping function is accomplished after the distribution function, the system is termed a distributed heat pump approach. Schematic representations of these two approaches are presented as Figures 1-1 and 1-2.

Ownership, operation and maintenance of the system can either be the responsibility of the waste energy producer, the users, a separate utility (either public or private), or shared among all concerned. The tradeoff studies between central and distributed heat pump strategies are based upon the assumption that either system is owned, operated, and maintained by a publically owned utility. This strategy has advantages from the ability to acquire low interest financing and to purchase equipment in large volume. User resistance to abandoning his existing equipment is lowered under conditions where minimal capital outlay is required. The utility can recover some of its capital outlay through a "connection charge" if detailed market penetration studies show a suitable fraction of potential users will accept such a charge.

The following paragraphs are devoted to discussions of the major subsystems for the two approaches.

WASTE ENERGY SOURCE AND ASSOCIATED HARDWARE

The system, as conceived, is not limited to any particular form of waste energy source. The most straightforward waste energy stream with which to deal is one borne by water, but gaseous energy carriers may be used at slight additional complexity. Water borne waste energy streams are the baseline approach. For the central heat pump approach, means must be arranged to support the heat pump evaporator in good thermal contact with the source. Contact will nominally be by immersion; hence, a trough or tank will form part of the energy source hardware. When dealing with highly corrosive or fouling waste waters, it may be more cost effective to arrange the evaporator tubing on the outside of the trough to achieve easier cleaning. The evaporator is still considered part of the heat pump subsystem, however.

CENTRAL HEAT PUMP APPROACH

DISTRIBUTED HEAT PUMP APPROACH

In many cases (food industry in particular), very significant amounts of hot water are used for daily washdown of equipment. Generally, such water is directly sewered. Means to collect and hold such water while energy is extracted will also be part of the energy source hardware, when required.

For the distributed heat pump approach, it will be possible to introduce the waste water directly to the district heating distribution system when the waste water is relatively clean. Other situations will require a heat exchanger at the source, as part of the source associated hardware.

Basic Heat Pump Cycles

There are a wide variety of refrigeration cycles which could be used in the reversed mode as heat pump systems for an HP-ICES. The current development status of the basic types are presented in Table 1-1. Details of the thermodynamic operation of the various potential heat pump systems can be found in standard thermodynamic textbooks.

Rankine cycle heat pumps are widely used in both residential and commercial applications for providing both space heating and space cooling. The available sizes for off-the-shelf equipment range from 1 ton to over 5,000 tons. The coefficient of performance (COP) of the heat pump varies depending upon relative temperatures of the source and sink, i.e. the thermal lift. Typical COP's range from 2 to 6. Rankine cycle heat pumps capable of providing up to 220°F thermal energy are commercially available.

Air cycle (reverse Brayton cycle) heat pumps are currently only in commercial use in aircraft air conditioning systems where their light weight offsets their lower performance compared to Rankine cycle heat pump systems. Development work is currently being performed to improve the performance and economics of air cycle heat pumps.

In steam jet systems, the mechanical compressor of the Rankine cycle heat pump systems is replaced with a steam ejector. Steam jet systems are currently only being used for cooling. Typical condenser temperatures are below 100°F. Typical COP for cooling ranges from 0.1 to 0.3 which limits the use of steam jet systems to applications where sources of low-cost steam are available.

Absorption cycle systems are widely used in commercial applications for providing space cooling in sizes ranging from 3 to over 600-ton capacity. Due to the low thermal rejection temperatures (typically below 100°F), there are no commercial absorption systems operating in the reversed mode to provide space heating. The primary advantage of absorption cycle systems is that they are driven by thermal energy rather than the higher quality electrical energy or mechanical shaft power required for Rankine cycle systems. Operational and economic factors limit the minimum driving thermal energy temperature to approximately 160°F. Thus, a heat source of 160°F or higher can be used to provide space cooling. Coefficient of performance achievable by these means, however, requires that the relatively low cost of the energy be very low.

Of the various heat pump systems examined, only the Rankine cycle systems are commercially in use for both space heating and cooling. In view of the development status, Rankine cycle systems were selected as the baseline by which to compare the central and distributed heat pump approaches.

Table 1-1
HEAT PUMP DEVELOPMENT STATUS

Type of Cycle	Development Status		Comments
	Heating	Cooling	
Rankine	Widespread commercial and residential use	Widespread and residential commercial use	COP's dependent upon source and sink temperatures, typically 2 to 6
Air cycle (Reverse Brayton)	Limited commercial use (aircraft)	Limited commercial use (aircraft)	Lower COP's than Rankine. Currently undergoing additional development to improve performance
Steam jet	Not currently used for heating	Limited commercial use	Limited commercial use due to low COP's, 0.1 to 0.3 for cooling
Absorption	Not currently used for heating	Widespread commercial use	COP's range from 0.5 to 1.1. Require 180°F + thermal energy source. Typical reject temperatures below 100°F

Topping and Backup Subsystem

Major assemblies in the topping and backup subsystem are the fossil fuel fired burner (assumed to be an oil burner), its associated controls, appropriate fuel storage tanks, hot and return water storage tanks, and associated control valving and instrumentation.

Both topping and storage functions act to extend the utilization of a given energy source. With no topping capability and no storage capability, the number of users that can be supplied is the quotient of the instantaneous minimum of energy available divided by the maximum instantaneous user demand. At all times, when the magnitude of the source is above minimum, some available energy will be wasted. Likewise, at all times when the user demand is less than maximum, available energy will be wasted.

Examining the annual load duration curve shown in Figure 1-3, it can be seen that by using small amounts of topping energy, a very significant increase in the amount of waste heat utilized can be achieved. Based upon European cogeneration/district heating systems, the economic tradeoff point is to have approximately 50 percent of the peak demand supplied by the topping system. Due to the shape of the demand curve, this design condition corresponds to approximately 90 percent of the total energy supplied being recovered waste heat and only 10 percent being supplied by the topping system.

Many industrial waste energy streams tend to be cyclical on a daily and weekly basis, following business hours. Storage is essential for this type of energy source in order to provide energy during nonproduction hours. As an example of this effect, Figure 1-4 shows the predicted energy furnished to a district heating system from a continuous waste energy stream. Energy provided is presented on the ordinate in dimensionless form as the ratio of energy provided by the system incorporating storage to that without storage. Storage capacity is presented on the abscissa as the ratio of storage capacity to annual energy recoverable. This work was performed for a specific energy stream and a specific demographic area (Intalco Aluminum Company and Bellingham, Washington), but does show the general trend.

Topping capability enhances system ability to provide service during an occasional extreme cold condition. The existence of this relatively inexpensive subsystem element, even though unused most of the time, allows the greater fraction of the capability of the storage unit to be exercised as less of the stored energy need by held in reserve against the possibility of unusual weather.

Storage System Concepts

Six basic types of thermal energy storage systems were examined in detail for use with the district hot water transmission system. These storage concepts were: 1) unpressurized hot water in steel tanks (storage temperature less than 212°F); 2) unpressurized hot water insulated heat storage ponds (less than 212°F); 3) moderately pressurized hot water tankage (212 to 250°F); 4) aquifer storage (less than 250°F); 5) unpressurized hot oil tankage; and 6) hot oil/rock hybrids (less than 275°F). Latent heat of fusion and rock bed thermal storage systems were ruled out initially due to their high cost.

TYPICAL ANNUAL LOAD DURATION CURVE

EFFECT OF THERMAL STORAGE ON
AVERAGE DISTRICT HEATING LOAD CAPABILITY

FROM REF. 29

Each of the various storage systems was evaluated on the basis of the following criteria:

- a. Initial storage system capital cost — \$/Btu of storage (based upon estimates shown in Figure 1-5)
- b. Recurring maintenance cost — \$/Btu/year (based upon initial cost and industrial experience where applicable)
- c. State of the art (subjective evaluation of degree to which storage system technology will be developed by the estimated wide-scale implementation date (1985) for district heating system)
- d. Safety, reliability, and potential environmental hazards (subjective evaluation)
- e. Peak storage temperature capability
- f. Site applicability — extent to which storage system is site specific, i.e., can only be used at some sites and not others
- g. Energy utilization (evaluation of the effect of storage system on the ability of system to maximize the energy recovery from the aluminum plant, i.e., seasonal storage capability)
- h. Storage efficiency (evaluation of the extent to which energy placed in the store can be recovered from the store).

The results of this evaluation effort are summarized in Table 1-2. The site applicability of aquifers was based upon a very preliminary study of known aquifers located in proximity to the various aluminum plants, and the aquifer storage efficiency was based upon efficiency estimates in the literature. The storage efficiencies of the other concepts were based upon detailed heat transfer analysis.

Comparing the three best storage systems (unpressurized hot water in steel tanks, aquifer storage, and heat storage ponds, respectively), the potentially lowest cost storage system is aquifer storage. The limited number of proven applicable sites and the fact that aquifer storage technology has not been reduced to engineering practice, resulted in a decision to base the remainder of this study upon the available technology of unpressurized steel tanks, recognizing that more favorable (economically) systems may result when aquifer technology becomes proven.

The cost optimization of the storage subsystem is dependent upon the consumer load duty cycle, population distribution, equipment costs, and the value of energy displacement. To obtain a minimum cost system, several detailed iterations on system and component sizing versus total energy supplied to the community must be conducted.

Distribution Subsystem

The distribution subsystem is comprised of all the piping, insulation, pumps, instrumentation, expansion loops, maintenance access ports and conduit necessary to transmit the energy recovered from the waste heat source to the users in the community.

INITIAL STORAGE SYSTEM CAPITAL COST

Table 1-2
STORAGE SYSTEM EVALUATION

Criteria	Weight	Hot H ₂ O (Steel Tank)	Pressurized H ₂ O	Aquifer Storage	Hot Oil	Hot Oil Hybrid	Hot H ₂ O Insulated Heat Storage Pond
Initial cost/Btu	3.0	7	4	10	1	2	8
Maintenance cost/Btu	2.0	8	7	7	9	7	7
State of the art	1.0	9	8	1	9	8	2
Safety	1.5	8	5	10	8	8	6
Reliability	2.0	9	9	7	9	9	9
Peak temperature capability	0.8	6	8	10	10	10	6
Environmental hazards	1.0	9	8	9	2	4	7
Storage density	0.5	5	6	3	3	4	5
Site applicability	2.0	10	10	5	10	10	10
Energy utilization	3.0	5	5	9	5	5	7
Storage efficiency	3.0	9	9	7	9	9	8
Total weighted score		154	133.7	148.5	133.5	134	146.3

Service Area

The characteristics of the service area which most strongly influence the distribution system are the peak energy use density and the degree to which the piping system installation process will be hampered by existing buried utilities and traffic patterns. At a later stage in this work, a specific area will be chosen for more detailed analysis; however, the current effort is to derive results with as general applicability as possible. To this end, the service area is described by an energy demand density and a medium degree of difficulty with excavation in urban areas. So that some intuitive feel for energy demand density is possible, this parameter is expressed as the equivalent number of single family residences per square mile. In actual fact, the subscribers are likely to be commercial establishments and medium to high rise residential structures, with perhaps some smaller individual demands mixed in. The effect of energy demand density is investigated over the range 1,500 residence equivalent/mi² to 6,000 residence equivalent/mi².

Current Technology

The cost of the distribution subsystem is the dominant item in the overall system cost, and may be as much as 70 percent of the total. For this reason, considerable attention is given to minimizing distribution subsystem costs, without compromising system life. Closed circuit hot water heat transmission/distribution networks are widely used in European district heating systems. In some U. S. cities (Hartford, Connecticut and Minneapolis, Minnesota), these networks are also used to provide a convenient heat sink for cooling by circulating chilled water. When both heat source and heat sink service is to be provided, a three or four pipe distribution network is required.

Large, over 200-mm (8 inches), underground trunk mains currently in use in Europe are usually laid in the prefabricated concrete conduits and insulated with mineral wool. Energy carrying capability varies by flow rates and temperature. The pipe joints are fully welded and are inspected by radiographic examination. Thermal insulation is applied to the pipes in the form of glass wool or mineral wool and the upper halves of the insulation covered with impervious plastic film. The pipes are supported by risers at intervals so that any water that accumulates can be drained. The conduits are covered by the reinforced concrete top element, and the whole is painted with waterproofing compound.

Smaller mains are laid in what is known as plastic conduit. This is commercially available pipe consisting of a steel inner pipe surrounded by insulation and covered with PVC or PE sheath. This main can be laid directly in the ground. The inner steel tubes are welded and then preformed insulation is applied over the joints, followed by a section of plastic sheath which is thermally shrunk into position over two O-rings.

Concerning underground pipes, it can be noted that for unusually damp conditions there is no solution that would be completely waterproof; the construction best suited is a trench lining cast on the site. For this reason, a sufficient downward slope should always be planned in the design, and the low points should have provisions for checking and draining the leakage water. The possibilities for water to leak into the duct system can be minimized if the right pipe route is chosen, taking into account the ground water level, flooding levels, etc. This would also decrease the risk of corrosion of the exterior pipe shield. Another way to decrease this risk is to arrange for appropriate outside drainage.

The gradual linking up of small distribution networks into one large network increases system reliability due to the possibilities opened up of alternative routes for the water in case of a main's failure. The mains are thus not laid radially from the heat source but are cross-coupled and ring-coupled so that a section can be isolated, if necessary, without interrupting the supply to other parts of the network. Valves are provided at tee-points to ensure that the flow reaches all parts of the system without stagnating anywhere or short circuiting.

In the United States, a number of companies make large (up to 32-inch diameter) prefabricated hot water distribution pipes for direct underground burial. These are available in a variety of materials and configurations.

In addition to the pipes themselves, the distribution system includes the supports (both fixed and expansion types and their supporting structures), the shutoff valves with which the network can be divided into sections, the valve housings, and the pipeline air vents and drainage systems. Very often much of this auxiliary equipment is assembled into substations and sited at strategic positions on a ring main system. The pipe channels or tunnels are ventilated using ducts at the highest and lowest points of the channel. Piping of any district heating system must also include provisions for accommodation of heat expansion. This is about 1.4 mm/m at a temperature difference of 120°C. To allow for heat expansion, both normal "U" type bends and axial expansion bellows are used. Bends, which require a great deal of space, are used when the piping route permits, whereas bellows are the most commonly used means allowing for heat expansion in the main pipework.

Costs

The cost of the distribution network is primarily a function of the following:

1. Number of users per unit area (user density)
2. Peak energy demand from the distribution network/user (i.e., the maximum rate of energy withdrawal by the user device)
3. Temperature drop in the distribution across network each user
4. Total number of users
5. Type of distribution network construction and insulation
6. Type and difficulty of the excavation required (i.e., rural or urban, rock or soil)

There are a wide variety of published costs for installed hot water distribution network pipes; some of these are summarized in Figure 1-6. The Burns and Roe cost curves are based upon insulated steel pipes cast in concrete. The Finnish and Swedish construction costs are based on construction methods in their respective countries. The Brookhaven costs are based upon the estimated installed costs in existing urban areas using polymer-lined concrete pipe. The Meador piping costs are estimated costs based upon prefabricated steel pipe within an insulated steel conduit. Figure 1-7 shows the cost of various current or proposed distribution networks for user densities. The cost data is presented as \$/million Btu/hr of user demand as a function of the peak distribution network demand density (million Btu/sq mi hr). The data has been normalized such that the average ΔT

COST OF BURIED PIPING

DISTRIBUTION NETWORK COSTS AS A FUNCTION AS A FUNCTION OF PEAK USER DEMAND DENSITY

across each user is identical ($\approx 105^{\circ}\text{F}$) for each system. The Finnish, Swedish, and Icelandic data are based upon historical construction costs for district heating systems in large cities.

Based upon discussions with two European district heating systems A/E firms, which are actively working in the United States on large-scale hot water district heating systems, the installed costs for the European systems will be very representative of U. S. district heating systems. The distribution network costs believed to be most representative and as such used in the HPOP computer code, are the Swedish distribution network costs supplied by Peter Margen of A. B. Atomenergi.

Future Developments

In the past several years it has become increasingly apparent that insulated fiberglass reinforced plastic (FRP) piping networks can be installed underground far more economically than insulated steel pipes. Currently, due to limited production, insulated FRP pipe is more expensive than insulated steel piping. The ability of FRP pipe to take up thermal expansion and contraction with its helical wound fibers eliminates the need for expansion loops and fittings required for steel pipes and thereby tends to make the installed cost of the FRP pipe less than the installed cost of the steel pipe. Reference 1 suggests that the eventual potential cost savings of FRP piping compared to steel piping may be as much as 50 percent. Currently, FRP pipe is only being produced in sizes up to 12-inch nominal diameter. As the market for the pipe grows, it is anticipated that larger sizes will be developed.

Prestressed concrete, as a pipe material, has great advantages in its strength, corrosion resistance, and cost. However, hot water can chemically attack the concrete and dissolve its constituents. Currently, work is being done in Europe (Reference 2) to develop a polymer-lined prestressed concrete pipe (PLPC) for hot water service. The polymer (plastic) lining protects the pipe from attack by the hot water, while the concrete pipe provides the necessary support to the liner.

The design of the PLPC pipes being developed incorporates an O-ring joint, such that the pipes can be just slipped together in the field to form a pipeline without the expensive and time consuming welding and radiographic inspection required for conventional steel pipe. The PLPC joints are also designed to absorb the thermal expansion and contraction of the pipe without additional expansion compensation devices.

The net effect of the lower PLPC piping material and assembly costs are that the estimated installed costs of a PLPC distribution network are only 1/3 as much as a conventional district heating system (References 2 and 3).

Due to its current development status, PLPC pipe may not be available for near-term construction. The predicted costs are based upon steel pipe in prefabricated concrete conduit, to yield conservative cost and payback estimate. It is possible, however, that PLPC will be available for national implementation of the waste heat/HP-ICES concept.

Piping Strategies – Two-Pipe Distribution Network System

Where both the heating and cooling needs of the community are to be supplied, the systems tend to become more complex; however, greater utilization may reduce unit energy costs. If the energy users in the community supplied by the system have as a group similar heating and cooling demands as a function of the ambient weather condition (for example, this would tend to be true of a group of similar residential structures), then their heating and cooling needs could be met by means of a two-pipe distribution network. Figure 1-18 shows schematically heating and cooling two-pipe distribution networks in both the centralized heat pump and distributed heat pump system configurations. During the winter, these systems would operate exactly like the heat only systems described in paragraph 2.2.1. During the summer, cold water would be circulated through the distribution network to provide cooling.

If a large cooling source such as a lake or a river were available which could accept the heat rejection from the system, the cooling towers shown in Figure 1-8 would not be required. For this type of case, the cooling loop would be run open cycle within the cooling source.

The major problem with a two-pipe distribution system is that if there is much diversity in the user community due to user location, shading or type of user, there will be times when a fraction of the user community will be demanding heating and at the same time the remainder of the user community requires cooling. Due to the limitations of a two-pipe distribution network, a centralized heat pump configuration can only supply either heating or cooling to the user community at any given time. With a distributed heat pump configuration system, however, heat and cooling can be supplied simultaneously to the user community.

With a two-pipe distributed heat pump configuration system during the summer months, the temperature in the distribution network could be lowered by using water from the cooling tower to optimize the cooling mode operation of the various system heat pumps. The small percentage of users who would require heating during these months could use their heat pumps to remove heat from the distribution network lines. The COP's of those units in the heating mode would be lower than they would be during the winter due to lower distribution line temperatures, but due to the limited heating demand, the effect on the overall system efficiency would be limited.

During the winter months, the system would be run in just the opposite fashion; i.e., the distribution line temperature would be optimized for heating mode operations of the system. Users requiring cooling during this time period could use their heat pumps in the cooling mode with a reduction from the summertime COP.

During the spring and fall, the distribution network temperatures would be optimized to maximize the overall energy efficiency of the HP-ICES system.

The major problem of varying the temperature in the distribution system is that except for when the temperatures are optimized for either pure cooling or pure heating, the various heat pumps in the system are running at less than optimal COP's with corresponding increases in electrical energy demand.

SCHEMATIC SYSTEM CONFIGURATIONS TWO PIPE DISTRIBUTION NETWORK WASTE HEAT/HP-ICES HEATING AND COOLING SYSTEMS

CENTRALIZED HEAT PUMP SYSTEM CONFIGURATION

DISTRIBUTED HEAT PUMP SYSTEM CONFIGURATION

As the demand for hot water continues throughout the year, and the required temperature is above the comfort temperature, all service supply from a central heat pump strategy is not possible with a two-pipe system.

Heating and Cooling Waste Heat/HP-ICES – Three- and Four-Pipe Distribution Network Systems

In those communities where there is a significant load diversity in the type of user connected to the system such that both significant cooling and heating loads must meet simultaneously, the most efficient system operation can be achieved by using three- and four-pipe distribution network systems, shown in Figures 1-9 and 1-10. The higher system efficiencies must be traded off against the additional cost of the extra distribution network piping.

A four-pipe distribution system is essentially two separate distribution networks – one strictly for heating and one strictly for cooling. The temperatures in each pair of distribution lines are optimized for their respective heating and cooling functions. Since the pipes would be laid in common trenches, the distribution network cost would be slightly less than double that of a two-pipe distribution network. When any user in the community required heating or cooling, he would either manually or automatically connect himself across the appropriate pair of lines in the distribution network.

The three-pipe system is essentially a modification of the four-pipe system in which a common return is used for both the heating and cooling lines. Using three pipes instead of four would reduce the distribution network cost by approximately 30%.

With centralized heat pump configuration systems, the common return line results in a mingling of the hot and cold return streams. Since the heat transfer fluids in the centralized heat pump system are recirculated, the comingling of the fluids results in additional cooling tower demands and in additional heating demands. During the summer and winter months (i.e., periods of maximum heating or cooling demand) when the overall system would be in a predominantly cooling or heating demand mode operation, the common return line would have little effect on the overall system performance or capacity.

With a distributed heat pump configuration system, the waste heat stream does not recirculate through the heating portion of the distribution and as such, the mingling of the heating and cooling streams does not affect the heating mode performance of the overall system. If a cooling tower is used for cooling mode operation, the comingling of the streams will result in increased cooling tower demands to provide the same return temperature in the cooling delivery line. If a large lake or river is being used as a cooling energy source, the comingling will not effect system performance compared to a four-pipe distribution system.

User Equipment Subsystems

The basic tradeoff study between central and distributed heat pump strategies is based upon the assumption that all user hookups are replacements of existing oil fired, forced air heating systems,

SCHEMATIC SYSTEM CONFIGURATIONS THREE PIPE DISTRIBUTION NETWORK WASTE HEAT/HP-ICES HEATING AND COOLING SYSTEM

CENTRALIZED HEAT PUMP SYSTEM CONFIGURATION

29011-96

DISTRIBUTED HEAT PUMP SYSTEM CONFIGURATION

SCHEMATIC SYSTEM CONFIGURATION FOUR PIPE DISTRIBUTION NETWORK WASTE HEAT/HP-ICES HEATING AND COOLING SYSTEM

CENTRALIZED HEAT PUMP SYSTEM CONFIGURATION

29011-94

DISTRIBUTED HEAT PUMP SYSTEM CONFIGURATION

29011-95

1-21

Figure 1-10

and electric hot water heaters. In an actual specific system design, a number of other types of heating systems will be encountered also, with varying degrees of complexity. In the following sections, the baseline user subsystem replacement equipment for central and distributed strategies is discussed, together with some notes concerning retrofitting of other types of existing heating systems.

Central Heat Pump Subsystem

Depending upon the type of user served and type of heating equipment currently installed (for retrofitted buildings), the specific design of the user subsystem for the central heat pump system will vary greatly. A typical user subsystem consists of two separate devices. One device provides space heating, and the second provides hot potable water. A schematic of the central heat pump user subsystem is shown in Figure 1-11.

The space heating systems used in the United States can be classified into four basic types:

1. Steam supplied
2. Direct electrical
3. Circulated hot water (hydronic)
4. Forced air.

Space heating systems currently using steam (primarily large offices and apartment buildings) can be converted to using the hot water supplied by the HP-ICES system by replacing the existing steam radiator with hot water convectors, and using the existing steam supply lines to carry the hot HP-ICES water to the convectors. Condensate return lines may be capable of taking the increased flow (at some increased pressure drop) as these are frequently oversized, i.e. a 3/4-inch pipe may have been installed where a 1/4-inch pipe would have carried the condensate load. Some additional control valves and pumps, as well as some additional piping (especially condensate return mains) might be required depending upon the current building system. To provide central cooling for this type of retrofit would probably require extensive pipe replacement.

The retrofit space heating applications, which can be converted over to a central HP-ICES system at minimum cost, are structures which currently use circulating hot water as the heat transfer medium within the building. For these buildings, the only modifications required are those associated with connecting up to the HP-ICES distribution network, and bypassing the existing building heating boilers.

While varying to some extent by region, the vast majority of United States residential homes and commercial buildings have forced air heating systems, i.e., heated air circulated through ductwork into the various parts of the structure. Conversion of these systems will require the installation of appropriately sized water-to-air heat exchangers in the existing duct system, probably in place of the existing furnace. This type of heat exchanger is widely used in the heating, ventilation, and air conditioning (HVAC) industry in conjunction with hydronic heating systems, and as such is commercially available in a wide variety of sizes and capacities. In a typical central heat pump system building retrofit, the size of the user subsystem duct heat exchanger will be selected to

**USER SUBSYSTEM SCHEMATIC
CENTRAL HEAT PUMP APPROACH**

produce duct temperatures compatible with the previous furnace system. Thus, the volume of air transferred by the ducts will be unchanged, duct velocities and pressure drops will be unchanged. This means that no significant duct work changes other than those required to install the heat exchanger are required.

Direct, electrically heated (nonforced air) structures will require the most significant building and heating modifications to provide space heating from the HP-ICES network. These modifications will typically include the installation heat exchangers (room convectors), fluid lines, and control valves.

New building and home construction can be easily integrated into the HP-ICES system with little or no impact on the structure designs, and potentially slight decreases in construction costs.

Potable hot water heating for all users will be provided by the HP-ICES system by means of special water-to-water heat exchangers. In their simplest form, these heat exchangers consist of a set of heat exchange coils inside an insulated tank, which replace the users' existing electric or fossil fuel fired hot water tanks. To avoid a potential health hazard, the heat exchangers must be designed such that in the event of a heat exchanger failure, the user potable water will not be contaminated. Heat exchangers (generally called double tube heat exchangers) meeting this requirement are commercially available.

Distributed Heat Pump Subsystem

The user subsystem for the distributed heat pump system consists primarily of a water-to-air, heat pump discussed in paragraph 1.2, or a water-to-water heat pump in the case where an existing hydronic system is retrofitted to a distributed HP-ICES. For new installations, models are available to be installed as part of a forced-air ductwork system in much the same fashion as an oil, gas, or electric furnace, and this can serve as a direct replacement.

Current practice for commercial water-to-air heat pumps is to design for duct air temperatures in the range of 100 to 115°F. Since the duct systems of most natural gas, oil fired, or electric furnaces are sized for 110 to 140°F duct air temperatures, ductwork may have to be changed in some retrofits, or higher duct velocities requiring higher fan power may be required.

Since domestic water heating represents a substantial portion of the total energy consumed by most users who would be connected to an HP-ICES system, it is desirable to accomplish as much as possible using the coefficient of performance gain with an HP-ICES system rather than direct fossil fuel or electrical water heating. One heat pump can be used to provide both space heating and hot water heating at the user site. While there are a number of ways this can be achieved, probably the simplest and most widely used approach is shown in Figure 1-12. A booster heater is used, if necessary, to increase the potable water temperature to the desired temperature. Due to the superheat in the compressor exhaust, the water temperature can be increased above the nominal heat pump condenser temperature. This space and hot water heating system, shown in Figure 1-22, was used as the basis for the Section 9.0 analyses assuming no electrical topping is required.

USER SUBSYSTEM SCHEMATIC DISTRIBUTED HEAT PUMP APPROACH

Excess Energy Dissipation

For systems which operate from industrial waste energy, and provide only heating functions (space and hot domestic water), the net effect of the system is to decrease the load upon existing dissipation means. Any excess in the magnitude of the waste energy source, which cannot be used or stored by the system will be dissipated by these existing means. This is a desirable degree of freedom in eliciting the cooperation of industrial concerns, i.e. the heat producer must be able to continue his operation independently regardless of the HP-ICES demand for (ability of the system to dissipate) heat.

When considering systems which provide both heating and cooling functions, there will be times when the cooling function exceeds the heating function, resulting in a net excess in low-grade energy production. This energy is either stored or dissipated by a cooling tower, depending upon the capacity of the thermal energy storage system being considered.

2.0 POTENTIAL APPLICATIONS

To date, no barriers have been identified in this study which would prohibit heat pump-assisted integrated community energy systems. Certain economic and technical factors will tend to limit the penetration of such systems into the space heating market, however, to those which show favorable return upon the capital invested in the system. Improvements over the current status, either economic or technical, will result in wider market penetration for the concept. In the following paragraphs, the baseline technical status and the baseline economic scenarios are described which lead to estimates of total market penetration.

Potential technical limitations could arise from excessive dependence upon rare raw materials, new or unproven technology, or by choice of a baseline system not representative of general conditions. Technical limitations from these effects have been avoided by choosing the baseline system under consideration to be constructed of common materials, to be composed of readily available, generally technically proven components, and to represent prevalent conditions regarding urban energy demand densities (2,944 users per square mile is equivalent to 7,500 square-foot lots, single family dwellings and 20 percent gross area devoted to streets, etc.; the demand range considered is from 1,500 equivalent users/mile square to 12,000 equivalent users/mile square).

The only technical limitation to the application of the HP-ICES concept is the availability of waste heat. Applying the first law of thermodynamics to the total energy use in the industrial sector yields staggeringly large amounts of energy available.

In actual fact, economic factors will tend to limit HP-ICES operating from industrial waste energy to those with sufficient payback to attract capital. The most influential technical variables leading to desirable economic performance are: 1) the distance between the energy source and users, 2) the source temperature, and 3) the user demand density of the use area. Two effects contribute to the latter. The population density and the demand per user, i.e., local weather characteristics.

The most influential economic variables on the economic performance of the system are the costs of fuel and electricity as they vary with time in relation to the general inflation rate. Another important factor is the cost of the distribution system. This cost can amount to as much as 70% of the total system cost. The dominant terms in the distribution system cost are the cost of pipe materials and the cost of pipe installation. The former may vary by a factor of 2 or 3 depending upon whether low-cost piping materials achieve their potential for durability. The latter can vary a great deal dependent upon the amount of interference with existing buried utility systems and the degree of difficulty experienced with obtaining pipeline right of way. For some installations in Europe, for instance, very inexpensive distribution systems have been built by running the mains directly through the adjoining basements of row housing developments. Not only is the excavation and backfill cost minimized by this technique, but the length of feeders to the individual heating devices is near zero as well.

Currently, the price of energy is increasing faster than the price of most other commodities. Extrapolating this trend indefinitely into the future, a favorable payback for any system will be predicted at some future time. High temperature waste energy sources, in close proximity to high density residential or commercial areas in northern latitudes, will be the first to attract capital. Unless unforeseen events reverse the rising trend of energy prices, even moderate temperature waste energy sources will eventually be used to supply distant low-density communities in mild climates. Reference 4 recommends an 8 percent per year escalation (above general inflation) in the price of fuel oil to the year 2000. This results in a 543 percent increase in the real price of fuel oil. This will be such a strong factor that substantially all waste energy source HP-ICES systems will show profitability by that date. The comparison between central and distributed strategies is valid as long as a consistent economic scenario is applied to both. In site-specific work, sensitivity analyses have been performed against fuel escalation rates, thereby avoiding excessive dependence upon assumed fuel escalation rates.

Two sources of low-grade energy are included in this study: industrial waste heat and electrical transformer reject heat. Electrical transformer substations are typically distributed throughout communities, and reject heat is capturable at 100° to 120°F. Quantities of reject heat vary from nominally 50 kilowatts (thermal) to in excess of 1 megawatt (thermal), thus providing ideal sources as distributed heat input. An estimated 6 to 10 million megawatt hours is currently rejected by major substation transformers. The major sources of energy are available from current waste energy sources exiting industrial plants in water streams.

Table 2-1 reproduces the result of an industrial waste energy survey (Reference 5). Columns 1 and 2 are energy potentially recoverable by HP-ICES systems. Columns 5 and 6 are potentially at least partly recoverable by these means, although the relatively high temperatures of these waste streams may yield better second law efficiencies through other energy conservation techniques. Columns 3 and 4 are relatively diffuse energy losses; in one case appearing as residual product energy and in the other as miscellaneous steam leakage.

The sum of Columns 1 and 2 yields over 2-3/4 quads potentially recoverable by HP-ICES without tapping the potential of gaseous industrial waste streams. Reference 5 estimates the temperature of the energy listed in Column 1 at $110 \pm 20^\circ\text{F}$ and that of Column 2 as $120 \pm 20^\circ\text{F}$. More recently, data is being gathered by Rocket Research Company concerning the waste energy dissipation of 150 larger industrial concerns in the three-state Pacific Northwest region. This sample represents 0.45 quad annual input energy, or 1.5 percent of the national total. A compilation of the data gathered during this survey is presented in Table 2-2. Column 2 compiles the water-borne waste energy, available above 70°F, the specified base temperature of that study. Assuming the 150-plant sample is representative of the nation, the 0.073-quad water-borne total yields a national estimate of 4.9 quads available. The physical number of systems will be dependent upon integration of the various sources and users. For example, the City of Seattle may have a single utility, but the system may have several distinct parts due to population density, geographic boundaries, etc. At this time, no barriers have been identified that would prevent any major metropolitan center within the United States from implementing this HP-ICES concept.

Table 2-1
INDUSTRIAL REJECT ENERGY PROFILE
(10¹² Btu/yr)

SIC	Industry	Waste Streams					
		110 ± 20°F Condenser Cooling Water	120 ± 20°F Contaminated Process Water	Product/ Process Losses	Condensate	Boiler Stack Exhaust	Furnace Exhaust
20	Food	290	175	260	14	105	150
21	Tobacco	3	0.5	4.5	0.5	2.5	1.5
22	Textile mills	29	15	109	6	52	18
23	Textile apparel	6	4	6	0.5	4	2
24	Lumber & wood	7	5	52	1	7	58
25	Furniture & fixtures	3	0.5	3	0.5	3	—
26	Paper & pulp	100	231	350	12	120	219
27	Publishing	8	12	11	1	6	15
28	Chemicals	125	60	425	26	135	125
29	Petroleum	80	380	1,470	52	245	840
30	Rubber	25	32	29	2	24	33
31	Leather	6	2.5	3.5	0.5	3	6
32	Stone, clay & glass	140	100	440	14	90	330
33	Primary metals	140	463	580	17.5	95	654
34	Fabricated metals	40.5	61	64	0.5	3	65
35	Nonelect. mach.	56	51	51	3	22	60
36	Elect. equip.	14.5	28.5	46	2	15	50
37	Transp. equip.	12	54.5	87	1	11	100
38	Instruments	9	2	12	1	10	7
39	Miscellaneous	6	5	13	0.5	5.5	13
	Totals	1,100	1,682.5	4,016	155.5	958	2,746.5

From Reference 5

Table 2-2
INDUSTRIAL WASTE HEAT SURVEY – HEAT LOSS SUMMARY

Industrial Classification	Number of Plants Surveyed	Gas Streams		Water Streams		Product Cooldown and Other	
		Loss, 10 ⁹ Btu/yr	Median Temp, °F	Loss, 10 ⁹ Btu/yr	Median Temp, °F	Loss, 10 ⁹ Btu/yr	Median Temp, °F
Paper	10	44,013	260	17,177	93	923	390
Aluminum	12	37,096	185	826	98	2,331	650
Refined petroleum	4	18,329	185	17,028	95	213	145
Misc. paper products	6	10,869	280	4,881	165	0	—
Pulp	6	13,356	215	7,786	95	409	575
Industrial chemicals	10	4,088	210	11,132	110	3,377	2,695
Saw mills	13	7,769	530	2,540	200	22	195
Plywood	13	10,265	350	4,096	235	57	195
Cement	8	7,680	420	353	84	1,128	385
Steel	8	2,676	1,210	1,761	104	848	2,060
Canned foods	6	205	220	36	83	2	115
Frozen foods	10	2,807	170	101	79	0	—
Dried foods	6	2,235	165	0	—	0	—
Meat	2	142	105	83	105	1	175
Misc wood products	2	1,002	1,690	0	—	0	—
Nonferrous metals	6	8,581	320	2,351	110	744	2,695
Beverages	2	637	105	197	75	0	—
Other food	7	2,995	212	1,496	135	0	—
Glass	2	461	615	43	85	3	135
Other manufacturers	1	12	795	110	95	0	—
Lightweight fabrication	1	170	2,495	105	135	0	—
Dairy	2	28	195	95	115	0	—
Motor vehicles	1	59	2,395	22	105	31	2,895
Finished chemicals	3	268	415	1,113	87	2	135
Textiles	2	32	400	17	177	0	—
Totals	143	175,775	283	73,349	114	10,091	1,540

From Reference 20

The coefficient of performance of a heat pump is strongly dependent upon the temperature of the energy source fluid leaving the evaporator and the temperature difference between evaporator and condenser. Assuming the condenser temperature is more or less fixed by heat transfer/flow characteristics of the user ductwork*, then the COP of the heat pump is a function only of the evaporator temperature, i.e., the temperature of source fluid leaving the evaporator. Figure 2-1 presents the overall system COP (i.e., district heating pump power has been added to the power required by the heat pump compressor, and heat losses have been subtracted from the total thermal output).

If energy from fuel oil burned in a furnace at η_B is to be replaced by waste heat pumped at a given COP, the energy required to drive the heat pump must be debited appropriately. Assuming this electrical energy is derived ultimately from a fuel oil burning facility at η_e , it can be shown that:

$$1 \text{ Btu furnished displaces } \frac{1}{\eta_B} \text{ of fuel}$$

and was composed of

$$\frac{1}{\text{COP}} \text{ Btu electrical energy}$$

$$\text{and } \frac{\text{COP} - 1}{\text{COP}} \text{ Btu withdrawn from the source.}$$

However, the electrical energy was generated at a fuel expense of

$$\frac{1}{\eta_e} \left(\frac{1}{\text{COP}} \right)$$

So that the net fuel savings is found as the difference between the fuel displaced and the fuel required:

$$\frac{1}{\eta_B} - \frac{1}{\eta_e} \left(\frac{1}{\text{COP}} \right)$$

*Achieving the same duct temperature as the conventional system will yield the same airflow rates, thus the same fan power, so that fan power cancels out the comparison analysis. This fixes the relationship between user heat exchanger area and condenser temperature. In order not to violate the fan power criterion, the heat exchanger area must be kept within bounds, which results in condenser temperatures approximately 10 to 20°F above the duct air temperature. Design duct temperatures vary per ASHRAE System Volume, Chapter 12, depending upon duct length from 110° to 140°F. The mid-range duct temperature of 125°F, coupled with the mid-range temperature difference of 15°F, yields a nominal condenser temperature of 140°F.

**EFFECT OF SOURCE REJECT TEMPERATURE
ON SYSTEM OVERALL COEFFICIENT OF PERFORMANCE IN HEATING MODE**

**CONDENSER TEMPERATURE = 140°F
LARGE CENTRAL HEAT PUMPS**

DATA FROM Ref. 17

To determine the total energy conservation potential of the HP-ICES concept, an energy ratio factor defined as fossil fuels conserved divided by waste energy utilized is calculated as:

$$\frac{\text{COP}}{\eta_B (\text{COP}-1)} - \frac{1}{\eta_e (\text{COP}-1)}$$

Choosing 70°F as a reasonable lower temperature limit yields 3.6 for COP from Figure 2-1. Choosing 60 percent as a representative oil burner efficiency and 30 percent as a representative power plant efficiency, the numerical value of the energy savings fraction calculates to 1.025. Thus, for this point design, each Btu utilized from a waste source will conserve 1.025 Btu's of fossil fuel. A parallel calculation with an oil burner efficiency of 50 percent yields 1.487 Btu's fossil fuel conserved per Btu withdrawn from waste energy. Note that this does not infer that a unit of waste energy is simply substituted for a larger quantity of fossil fuel energy. Rather, the higher fuel efficiency of the heat pump can deliver energy to the user space at a considerable fuel savings over the relatively inefficient oil burner.

The aggregate energy available from Reference 5 is 2.8×10^{15} Btu's available above 70°F. The resultant national fuel savings is predicted at 2.87×10^{15} Btu/year. Taking the heating value of fuel oil at 140,000 Btu/gallon, 42 gallons/barrel yield a bulk fuel savings of 488×10^6 barrels/year for coupling HP-ICES to existing water-carried industrial waste heat. This energy availability can be substantially increased by including other industrial waste heat sources such as product cooldown and excess stack heat as additional baseload sources or peaking sources; however, system complexity (and costs) also increase. In addition, some decrease in availability will also occur due to source proximity to the user, water contamination level at the source, and mismatch of availability and load. These latter factors tend to be economic trade-offs and not technical barriers. It is anticipated that the projected fuel savings of 2.87×10^{15} Btu/year will be conservative as the 150-plant sample, extrapolated to the nation as a whole predicts nearly double that figure.

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3.0 EXPECTED SYSTEM PERFORMANCE, GENERALIZED SYSTEMS

The performance of three systems is compared on a first law energy basis and a second law availability basis in this section. For comparison purposes, the numbers are for the supply of space and water heating demand equivalent to the demand of 1,000 single family residences over the standard year in the Seattle area. The conventional alternate system, fuel oil burning furnaces, does not reflect the energy expenditure for fuel oil delivery, and, thus, presents slightly high efficiencies. For the two HP-ICES arrangement, the comparative energy and work terms (district heating pump power and line thermal losses) are included.

The reference temperature used for availability calculations is 52°F, the mean ground water temperature in the Seattle area. Availability is calculated as the work producible by a Carnot engine drawing the amount of energy in question for an infinite energy reservoir at the temperature in question, and rejecting energy to the reference state. A 95 percent conversion efficiency to work is assumed for electrical energy. The temperature achievable in fuel oil combustion is taken as 3,100°F.

The first law and second law efficiencies for the three systems are summarized in Table 3-1.

Table 3-1
EFFICIENCY SUMMARY

	First Law Efficiency	Second Law Efficiency	Ratio of Second Law Efficiencies HP-ICES/Conventional
Conventional system	0.60	0.0173	
HP-ICES distributed	0.989	0.0612	3.5
HP-ICES central	0.972	0.0865	5.0

Conventional oil furnaces burn fuel inefficiently with average energy efficiencies of 50 to 60 percent (References 6 and 7). These low efficiencies are primarily the result of incomplete combustion and stack losses. Another important consideration of burning oil to provide space and hot water heating is the loss of second law of thermodynamics availability (i.e., the degradation in the ability of the energy to perform work). If oil is burned under the appropriate conditions, the high grade thermal energy inherent in the combustion flame can be used to produce shaft work, electricity, or used to meet high availability thermal requirements such as high temperature melting/material processing considerations. The first and second law performance of conventional oil furnaces for 1,000 residential users in the Seattle, Washington area are shown in the energy flow

and energy availability diagram, Figures 3-1 and 3-2. While the first law efficiency of the home oil furnace is 60 percent, the second law efficiency which is indicative of the true energy conversion efficiency is only 1.73 percent.

For the HP-ICES systems being examined, both the distributed and central heat pump systems take low availability thermal energy (waste heat), and utilizing proportionately small amounts of high availability energy (electricity), raise the thermal energy to a temperature such that it can be used by a consumer. The first law and second law energy flow diagrams for the distributed heat pump system are presented in Figures 3-3 and 3-4, respectively. Corresponding diagrams for the central heat pump are presented in Figures 3-5 and 3-6. The central and distributed heat pump flow diagrams are based upon meeting the same user energy demands as was used as the basis (i.e., 1,000 residential users) for the conventional oil furnace energy diagrams shown in Figures 3-1 and 3-2.

As shown in Figures 3-3 and 3-4, both the distributed heat pump and central heat pump systems very efficient on a first law basis. The only energy loss is the heat loss from the pipes in the distribution network which amounts to only 2.76 and 1.1 percent for the respective HP-ICES systems.

On a second law basis, the differences between the various systems are even more apparent. The second law efficiencies for the distributed heat pump and central heat pump systems are 3.53 and 5.00 times higher than that of a conventional oil furnace. The difference in second law efficiency between the distributed heat pump and the central heat pump systems is primarily the result of the higher efficiency of the central heat pump unit as opposed to the lower efficiency of the distributed system user heat pumps. The higher efficiency (higher COP) of the central heat pump unit is primarily the result of larger size and the economies of scale which make it practical to maximize the performance of the heat pump without occurring an undue cost penalty.

ENERGY DIAGRAMS

ENERGY DIAGRAM CONVENTIONAL OIL FURNACES

Figure 3-1

29016-96A

ENERGY DIAGRAM DISTRIBUTED HP-ICES

Figure 3-3

29016-98A

ENERGY DIAGRAM CENTRAL HP-ICES

Figure 3-5

29016-97A

AVAILABILITY DIAGRAMS

AVAILABILITY DIAGRAM CONVENTIONAL OIL BURNER

Figure 3-2

29016-95A

AVAILABILITY DIAGRAM DISTRIBUTED HP-ICES

Figure 3-4

29016-93A

AVAILABILITY DIAGRAM CENTRAL HP-ICES

Figure 3-6

29016-94A

4.0 EXPECTED ECONOMIC PERFORMANCE, GENERALIZED SYSTEMS

BASELINE SYSTEMS

The economic analysis of distributed and central HP-ICES configurations is based upon a 1985 start date. A 30-year life typical of utility practice is assumed. A general inflation rate of 5 percent, a labor escalation rate of 6 percent, and a discount rate of 8 percent are used for the baseline calculations. Following the recommendation of Reference 4, fuel oil is assumed to escalate at 8 percent above the general inflation rate, i.e., $1.05 \times 1.08 - 1$ or 13.4 percent. The escalation rate for electrical energy is found from the average of Reference 4, regional figures at 6.21 percent above the underlying inflation rate, i.e., $(1.062)(1.05) - 1$ or 11.4 percent.

For the conventional alternate system used for comparative analysis, fuel oil burners are assumed to have a 10-year life (per the recommendation of ASHRAE Handbook and Product Directory 1975 September); thus, two complete replacements occur during the period of comparison.

Total annual system costs for the conventional alternate system are composed of the capital costs of the burners amortized over their lifetimes, costs for operation and maintenance, and the cost of fuel. This total represents the maximum possible total which could be changed by an HPICES, i.e., the rate structure where subscriber economic incentive to join the system is neither negative nor positive.* For this analysis, the HPICES sales are defined as equal to this total for the conventional system; thus when the same analysis routine is applied to the conventional system, the net (cash flow) and net present value are identically zero.

As the capital for first investment is borrowed at 8 percent interest rate and amortized over the system life, the internal rate of return is also 8 percent. This is conservatively consistent with current public utility financing opportunities at 6.5 percent.

Table 4-1 presents the results of the life cycle cost analysis for the conventional alternate system. For reference, the cost of energy delivered to the user space is tabulated in the ninth column. Base dollars referred to in Tables 4-1 through 4-3 are 1985 dollars.

The results of life cycle cost analysis on an example distributed configuration and on an example central configurations are presented in Tables 4-2 and 4-3, respectively. Sales for these systems are defined as equal to sales (and, therefore, expenses) for the conventional alternate system. Capital costs are the payments necessary to pay off the system first cost over its lifetime. The lifetime of distributed heat pump units is taken at 10 years, as recommended by Reference 8; hence, two replacements occur during the comparison period. The economic life of the larger heat pumps required for the central heat pump systems is estimated at 15 years as recommended by Reference 17, yielding one replacement during the system lifetime.

*Other incentives do exist, for example reduced fire hazard, decreased atmospheric pollution, and national energy savings. It is recognized that these alone are unlikely to result in universal subscriber acceptance. Rather, the intent of this analysis is to present the total cost difference between the two systems from an overview position. System viability can thus be assessed independently of assumptions regarding how the dollar savings are to be shared among the energy supplier, the utility, and the subscribers.

CONVENTIONAL OIL FURNACE
ECONOMIC ANALYSES
VERSION 2.0

Table 4-1

ASSUMPTIONS

CURRENT ENERGY COSTS (BASE DOLLARS)

USER ENERGY COST (\$/10⁶ BTU) 3.571 (CONSUMED AT .60 EFFICIENCY)
FOSSIL TOPPING COST (\$/GAL) .3998 (NO.6 FUEL OIL CONSUMED AT 0.85 EFFICIENCY)
PUMP AND FAN ENERGY COST (\$/KW-HR) .0400

PLANT LIFE (YEARS) 30.00 (START OF PLANT OPERATION - 1985)

AFTER TAX COST OF CAPITAL .0800

ESCALATION RATES

GENERAL INFLATION RATE/YEAR .0500
LABOR ESCALATION RATE/YEAR .0600
FOSSIL ENERGY ESCALATION RATE/YEAR .1340
ELECTRICAL ESCALATION RATE/YEAR .1140

NET PRESENT VALUE AT 0.08 = .0
INTERNAL RATE OF RETURN = 8.0000E-02

TOTAL SYSTEM COST (\$1985) AT START OF SYSTEM OPERATION 1.1257E+06

YEAR	SALES	CAP. COSTS	OPERATION	FUEL	LOAN INT	NET	LOANS	\$/BTU UTIL.	PV AT .08
1985	1.2432E+06	1.6776E+05	1.1277E+05	9.6265E+05	.0	.0	.0	1.8537E-05	.0
1986	1.3789E+06	1.6776E+05	1.1954E+05	1.0916E+06	.0	.0	.0	2.0562E-05	.0
1987	1.5324E+06	1.6776E+05	1.2671E+05	1.2379E+06	.0	.0	.0	2.2850E-05	.0
1988	1.7059E+06	1.6776E+05	1.3431E+05	1.4038E+06	.0	.0	.0	2.5437E-05	.0
1989	1.9020E+06	1.6776E+05	1.4237E+05	1.5919E+06	.0	.0	.0	2.8362E-05	.0
1990	2.1239E+06	1.6776E+05	1.5091E+05	1.8052E+06	.0	.0	.0	3.1670E-05	.0
1991	2.3749E+06	1.6776E+05	1.5997E+05	2.0471E+06	.0	.0	.0	3.5412E-05	.0
1992	2.6588E+06	1.6776E+05	1.6957E+05	2.3214E+06	.0	.0	.0	3.9646E-05	.0
1993	2.9800E+06	1.6776E+05	1.7974E+05	2.6325E+06	.0	.0	.0	4.4436E-05	.0
1994	3.3436E+06	1.6776E+05	1.9053E+05	2.9853E+06	.0	.0	.0	4.9857E-05	.0
1995	3.8605E+06	2.7326E+05	2.0194E+05	3.3853E+06	.0	.0	.0	5.7566E-05	.0
1996	4.3263E+06	2.7326E+05	2.1404E+05	3.8344E+06	.0	.0	.0	6.4510E-05	.0
1997	4.8535E+06	2.7326E+05	2.2692E+05	4.3533E+06	.0	.0	.0	7.2373E-05	.0
1998	5.4505E+06	2.7326E+05	2.4054E+05	4.9367E+06	.0	.0	.0	8.1274E-05	.0
1999	6.1264E+06	2.7326E+05	2.5497E+05	5.5982E+06	.0	.0	.0	9.1354E-05	.0
2000	6.8919E+06	2.7326E+05	2.7027E+05	6.3484E+06	.0	.0	.0	1.0277E-04	.0
2001	7.7588E+06	2.7326E+05	2.8648E+05	7.1991E+06	.0	.0	.0	1.1569E-04	.0
2002	8.7407E+06	2.7326E+05	3.0367E+05	8.1637E+06	.0	.0	.0	1.3034E-04	.0
2003	9.8528E+06	2.7326E+05	3.2189E+05	9.2577E+06	.0	.0	.0	1.4692E-04	.0
2004	1.1113E+07	2.7326E+05	3.4120E+05	1.0498E+07	.0	.0	.0	1.6570E-04	.0
2005	1.2712E+07	4.4512E+05	3.6168E+05	1.1905E+07	.0	.0	.0	1.8955E-04	.0
2006	1.4329E+07	4.4512E+05	3.8338E+05	1.3500E+07	.0	.0	.0	2.1366E-04	.0
2007	1.6161E+07	4.4512E+05	4.0638E+05	1.5309E+07	.0	.0	.0	2.4098E-04	.0
2008	1.8237E+07	4.4512E+05	4.3076E+05	1.7361E+07	.0	.0	.0	2.7193E-04	.0
2009	2.0589E+07	4.4512E+05	4.5661E+05	1.9687E+07	.0	.0	.0	3.0701E-04	.0
2010	2.3254E+07	4.4512E+05	4.8400E+05	2.2325E+07	.0	.0	.0	3.4675E-04	.0
2011	2.6275E+07	4.4512E+05	5.1304E+05	2.5317E+07	.0	.0	.0	3.9179E-04	.0
2012	2.9698E+07	4.4512E+05	5.4383E+05	2.8709E+07	.0	.0	.0	4.4284E-04	.0
2013	3.3578E+07	4.4512E+05	5.7646E+05	3.2556E+07	.0	.0	.0	5.0069E-04	.0
2014	3.7975E+07	4.4512E+05	6.1104E+05	3.6919E+07	.0	.0	.0	5.6625E-04	.0

DISTRIBUTED SYSTEM
ECONOMIC ANALYSES
VERSION 2.0

Table 4-2

ASSUMPTIONS

CURRENT ENERGY COSTS (BASE DOLLARS)

USER ENERGY COST (\$/10E6 BTU) 3.571 (CONSUMED AT .60 EFFICIENCY)
FOSSIL TOPPING COST (\$/GAL) .3998 (NO6 FUEL OIL CONSUMED AT 0.85 EFFICIENCY)
PUMP AND FAN ENERGY COST (\$/KW-HR) .0400

PLANT LIFE (YEARS) 30.00 (START OF PLANT OPERATION - 1985)

AFTER TAX COST OF CAPITAL .0800

ESCALATION RATES

GENERAL INFLATION RATE/YEAR .0500
LABOR ESCALATION RATE/YEAR .0600
FOSSIL ENERGY ESCALATION RATE/YEAR .1340
ELECTRICAL ESCALATION RATE/YEAR .1140

NET PRESENT VALUE AT 0.08 = 1.7185E+07
INTERNAL RATE OF RETURN = .1175

TOTAL SYSTEM COST (1985) AT START OF SYSTEM OPERATION 8.9773E+06

YEAR	SALES	CAP. COSTS	OPERATION	FUEL	LOAN INT	NET	LOANS	\$/BTU UTIL.	PV AT .08
1985	1.2432E+06	9.4109E+05	7.5296E+05	.0	.0	-4.5088E+05	.0	2.5261E-05	-4.1748E+05
1986	1.3789E+06	9.4109E+05	1.0580E+06	.0	3.6070E+04	-6.5626E+05	4.5088E+05	2.9810E-05	-5.3172E+05
1987	1.5324E+06	9.4109E+05	1.1566E+06	.0	8.8571E+04	-6.5388E+05	1.1071E+06	3.1280E-05	-4.4874E+05
1988	1.7059E+06	9.4109E+05	1.2652E+06	.0	1.4088E+05	-6.4131E+05	1.7610E+06	3.2899E-05	-3.6783E+05
1989	1.9020E+06	9.4109E+05	1.3849E+06	.0	1.9219E+05	-6.1614E+05	2.4023E+06	3.4684E-05	-2.8853E+05
1990	2.1239E+06	9.4109E+05	1.5169E+06	.0	2.4148E+05	-5.7556E+05	3.0185E+06	3.6652E-05	-2.1053E+05
1991	2.3749E+06	9.4109E+05	1.6625E+06	.0	2.8752E+05	-5.1627E+05	3.5940E+06	3.8823E-05	-1.3347E+05
1992	2.6588E+06	9.4109E+05	1.8452E+06	.0	3.2882E+05	-4.5632E+05	4.1103E+06	4.1547E-05	-6.8881E+04
1993	2.9800E+06	9.4109E+05	2.0486E+06	.0	3.6533E+05	-3.7501E+05	4.5666E+06	4.4580E-05	-4843
1994	3.3436E+06	9.4109E+05	2.2752E+06	.0	3.9533E+05	-2.6808E+05	4.9416E+06	4.7960E-05	5.8439E+04
1995	3.8605E+06	1.1647E+06	2.5277E+06	.0	4.1678E+05	-2.4871E+05	5.2047E+06	5.5059E-05	7.2082E+04
1996	4.3263E+06	1.1647E+06	2.6527E+06	.0	4.3667E+05	7.2166E+04	5.4584E+06	5.6923E-05	2.0207E+05
1997	4.8535E+06	1.1647E+06	2.9174E+06	.0	4.3090E+05	3.4045E+05	5.3862E+06	6.0871E-05	2.8362E+05
1998	5.4505E+06	1.1647E+06	3.2103E+06	.0	4.0366E+05	6.7179E+05	5.0458E+06	6.5238E-05	3.6615E+05
1999	6.1264E+06	1.1647E+06	3.5343E+06	.0	3.4992E+05	1.0774E+06	4.3740E+06	7.0070E-05	4.4996E+05
2000	6.8914E+06	1.1647E+06	3.8930E+06	.0	2.6373E+05	1.5704E+06	3.2966E+06	7.5418E-05	5.3536E+05
2001	7.7588E+06	1.1647E+06	4.2902E+06	.0	1.3810E+05	2.1658E+06	1.7262E+06	8.1341E-05	6.2286E+05
2002	8.7407E+06	1.1647E+06	4.7676E+06	.0	.0	2.8084E+06	.0	8.8459E-05	7.0279E+05
2003	9.8528E+06	1.1647E+06	5.2993E+06	.0	.0	3.3888E+06	.0	9.6387E-05	7.8523E+05
2004	1.1113E+07	1.1647E+06	5.8915E+06	.0	.0	4.0564E+06	.0	1.0522E-04	8.7029E+05
2005	1.2712E+07	1.5291E+06	6.5514E+06	.0	.0	4.6313E+06	.0	1.2049E-04	9.2003E+05
2006	1.4329E+07	1.5291E+06	7.0195E+06	.0	.0	5.7801E+06	.0	1.2747E-04	1.0632E+06
2007	1.6161E+07	1.5291E+06	7.7554E+06	.0	.0	6.8763E+06	.0	1.3844E-04	1.1711E+06
2008	1.8237E+07	1.5291E+06	8.5717E+06	.0	.0	8.1358E+06	.0	1.5062E-04	1.2830E+06
2009	2.0589E+07	1.5291E+06	9.4773E+06	.0	.0	9.5824E+06	.0	1.6412E-04	1.3992E+06
2010	2.3254E+07	1.5291E+06	1.0482E+07	.0	.0	1.1843E+07	.0	1.7910E-04	1.5201E+06
2011	2.6275E+07	1.5291E+06	1.1597E+07	.0	.0	1.3148E+07	.0	1.9573E-04	1.6460E+06
2012	2.9698E+07	1.5291E+06	1.2899E+07	.0	.0	1.5269E+07	.0	2.1515E-04	1.7694E+06
2013	3.3578E+07	1.5291E+06	1.4350E+07	.0	.0	1.7699E+07	.0	2.3678E-04	1.8994E+06
2014	3.7975E+07	1.5291E+06	1.5966E+07	.0	.0	2.0480E+07	.0	2.6087E-04	2.0353E+06

CENTRAL SYSTEM
ECONOMIC ANALYSES
VERSION 2.0

Table 4-3

ASSUMPTIONS

CURRENT ENERGY COSTS (BASE DOLLARS)
USER ENERGY COST (\$/10E6 BTU) .3571
FOSSIL TOPPING COST (\$/GAL) .3998
PUMP AND FAN ENERGY COST (\$/KW-HR) .0400

(CONSUMED AT .60 EFFICIENCY)
(NO6 FUEL OIL CONSUMED AT 0.85 EFFICIENCY)

PLANT LIFE (YEARS)

30.00 (START OF PLANT OPERATION - 1985)

AFTER TAX COST OF CAPITAL

.0800

ESCALATION RATES

GENERAL INFLATION RATE/YEAR .0500
LABOR ESCALATION RATE/YEAR .0600
FOSSIL ENERGY ESCALATION RATE/YEAR .1340
ELECTRICAL ESCALATION RATE/YEAR .1140

NET PRESENT VALUE AT 0.08 = 3.3699E+07
INTERNAL RATE OF RETURN = .2131

TOTAL SYSTEM COST (\$1985) AT START OF SYSTEM OPERATION 5.6706E+06

YEAR	SALES	CAP. COSTS	OPERATION	FUEL	LOAN INT	NET	LOANS	\$/BTU UTIL.	PV AT .08
1985	1.2432E+06	5.4705E+05	6.3765E+05	.0	.0	5.8481E+04	.0	1.7665E-05	5.4149E+04
1986	1.3789E+06	5.4705E+05	6.9427E+05	.0	.0	1.3762E+05	.0	1.8510E-05	1.1799E+05
1987	1.5324E+06	5.4705E+05	7.5647E+05	.0	.0	2.2887E+05	.0	1.9437E-05	1.8169E+05
1988	1.7059E+06	5.4705E+05	8.2482E+05	.0	.0	3.3401E+05	.0	2.0456E-05	2.4550E+05
1989	1.9020E+06	5.4705E+05	8.9998E+05	.0	.0	4.5501E+05	.0	2.1577E-05	3.0967E+05
1990	2.1239E+06	5.4705E+05	9.8267E+05	.0	.0	5.9418E+05	.0	2.2810E-05	3.7443E+05
1991	2.3744E+06	5.4705E+05	1.0737E+06	.0	.0	7.5411E+05	.0	2.4168E-05	4.4001E+05
1992	2.6588E+06	5.4705E+05	1.1739E+06	.0	.0	9.3777E+05	.0	2.5662E-05	5.0665E+05
1993	2.9800E+06	5.4705E+05	1.2844E+06	.0	.0	1.1486E+06	.0	2.7309E-05	5.7457E+05
1994	3.3436E+06	5.4705E+05	1.4062E+06	.0	.0	1.3903E+06	.0	2.9125E-05	6.4400E+05
1995	3.8605E+06	5.4705E+05	1.5405E+06	.0	.0	1.7730E+06	.0	3.1127E-05	7.6042E+05
1996	4.3263E+06	5.4705E+05	1.6886E+06	.0	.0	2.0906E+06	.0	3.3337E-05	8.3021E+05
1997	4.8535E+06	5.4705E+05	1.8522E+06	.0	.0	2.4543E+06	.0	3.5776E-05	9.0245E+05
1998	5.4505E+06	5.4705E+05	2.0324E+06	.0	.0	2.8707E+06	.0	3.8464E-05	9.7735E+05
1999	6.1264E+06	5.4705E+05	2.2323E+06	.0	.0	3.3471E+06	.0	4.1443E-05	1.0552E+06
2000	6.8919E+06	5.4705E+05	2.4524E+06	.0	.0	3.8921E+06	.0	4.4731E-05	1.1361E+06
2001	7.7588E+06	5.4705E+05	2.6965E+06	.0	.0	4.5153E+06	.0	4.8366E-05	1.2203E+06
2002	8.7407E+06	5.4705E+05	2.9660E+06	.0	.0	5.2276E+06	.0	5.2385E-05	1.3082E+06
2003	9.8528E+06	5.4705E+05	3.2643E+06	.0	.0	6.0415E+06	.0	5.6832E-05	1.3994E+06
2004	1.1113E+07	5.4705E+05	3.5943E+06	.0	.0	6.9713E+06	.0	6.1753E-05	1.4957E+06
2005	1.2712E+07	1.1074E+06	4.8577E+06	.0	.0	6.7466E+06	.0	6.8944E-05	1.6037E+06
2006	1.4329E+07	1.1074E+06	5.3116E+06	.0	.0	7.9097E+06	.0	9.5716E-05	1.6549E+06
2007	1.6161E+07	1.1074E+06	5.8117E+06	.0	.0	9.2416E+06	.0	1.0317E-04	1.5740E+06
2008	1.8237E+07	1.1074E+06	6.3631E+06	.0	.0	1.0766E+07	.0	1.1140E-04	1.6978E+06
2009	2.0584E+07	1.1074E+06	6.9713E+06	.0	.0	1.2510E+07	.0	1.2046E-04	1.8267E+06
2010	2.3254E+07	1.1074E+06	7.6423E+06	.0	.0	1.4505E+07	.0	1.3047E-04	1.9610E+06
2011	2.6275E+07	1.1074E+06	8.3829E+06	.0	.0	1.6784E+07	.0	1.4151E-04	2.1012E+06
2012	2.9698E+07	1.1074E+06	9.2009E+06	.0	.0	1.9390E+07	.0	1.5371E-04	2.2475E+06
2013	3.3578E+07	1.1074E+06	1.0105E+07	.0	.0	2.2366E+07	.0	1.6719E-04	2.4005E+06
2014	3.7975E+07	1.1074E+06	1.1103E+07	.0	.0	2.5764E+07	.0	1.8208E-04	2.5604E+06

Operational costs include the cost of electrical energy to power the compressors and distribution pumps, as well as labor for maintenance.

Fuel costs will show the cost of oil burned in the topping-backup boiler for those systems which show its use. For both example systems, the magnitude of the source was sufficient to meet all user demands during the example year; hence, no fuel costs are shown.

The columns entitled LOAN and LOAN INT take care of situations where the system operates at a loss for some years. It is assumed that short-term capital to cover such losses can be borrowed at the discount rate. The column entitled NET presents sales less capital cost, operating costs, fuel costs and interest on short term loans. A running total of the short-term loan principal is presented as LOANS. All positive net is applied toward returning any short-term loan outstanding.

The cost per unit of energy furnished is presented in the ninth column called \$/BTU UTIL.

The present value of the cash flow before short-term interest payments and loan payback payments, discounted at 8 percent back to the start date, is presented in the final column. As the effect of the operating loss is entered as a negative present value when incurred, to list the present value of the net (after payback) would debit the present value column twice for the same short-term loss. The sum of the entries in the present value column is the net present value as the original investment has been paid off through the annuity entitled CAP COSTS.

The two sample systems, central and distributed, both show economic advantages over the conventional alternate. Both HP-ICES systems satisfy the hot water and space heating demands for 1,000 users, decreasing the temperature of a waste water source by 10 degrees from 100 to 90°F. In the distributed case, it is assumed that the waste water stream is diverted directly into the distribution network, avoiding the cost of a heat exchanger at the source. A constant source magnitude was assumed so that storage is unnecessary, though the cost of an oil fired topping and backup boiler is included in both systems.

The central arrangement shows profitability from the start of operation, and accumulates a net present value of over 30 million dollars over a 30-year lifetime. The distributed system operates at a loss for the first 10 years, pays back its early operational losses by the fifteenth year, and shows profitability for the second half of its lifetime, accumulating a net present value of approximately half that of the central system. The central arrangement supplies energy at 58 percent to 70 percent of the cost of energy supplied by the distributed system.

A word of caution is in order concerning comparison of the two HP-ICES concepts. The two example cases were chosen to supply identical demands, and to utilize as near as possible, the same fraction of available waste energy from the source, yielding the same lift required of heat pumps in both cases.

Neither system is optimized to bring out its particular advantages; hence, considerable improvement in the economic parameters may be possible for both systems.

Variations in demand patterns for different areas of the country will also effect the optimum designs, hence the economic parameters. User density is another important variable, the effect of which must be quantified. This economic analysis methodology will be used to analyze the site specific systems and determine the effects of various sensitivity parameters.

COMPARISON OF CENTRAL TO DISTRIBUTED HEAT PUMP STRATEGY

The best known common denominators by which widely differing systems can be compared are economic ones. Thus, a hypothetical system providing space heating and hot domestic water production can be evaluated against one which provides space heating only; or one which provides space heating, hot domestic water and space cooling in another geographic region; or with a different heat pump strategy.

A convenient parameter by which to evaluate systems is the ratio of total capital cost to annual energy furnished. This relatively simple economic parameter indicates the trends of all economic criteria without dependence upon assumptions regarding future value of energy, labor, etc.

Secondary variables of interest for the comparison of central to distributed strategy are: type of service provided and energy demand density. Energy demand density further depends upon the equivalent number of users per unit area and local weather characteristics defining the demand per equivalent user. In Figure 4-1 the two heat pump location strategies are compared for the effect of demand density (effective number of users per square mile) with the effect of weather pattern constant (Seattle Weather Pattern) and for a system which provides space heating and the production of hot domestic water, but does not provide space cooling. The central strategy is seen to have an advantage across the board. Two effects contribute to this advantage – the higher performance coefficient achievable with the larger central heat pumps, and the fact that a greater temperature difference is achieved in the district heating water for the central case, requiring less water to be pumped through the system.

The effect of differing weather patterns upon the central and distributed heat pump strategies is presented in Figure 4-2, for the space heating only service option. Five cities were chosen for varying total space heating demand. User density is held constant at 2,944 users (effective) per square mile. The central strategy shows economic advantage throughout the spectrum. Southern cities with low annual heating demands show relatively high expense compared to more northerly cities.

Figure 4-3 presents the same tradeoff for the service option which provides both space heating and domestic hot water production. Again, the central strategy is beneficial. Inclusion of hot water service decreases the cost per million Btu furnished for all weather patterns.

Figure 4-4 presents the central or distributed strategy for the all-service option, space heating, space cooling, and domestic water production. For this case, the distributed strategy is more beneficial. The increased expense associated with additional distribution piping to provide the cooling function in the central strategy is the primary reason for the difference.

**COMPARISON OF CENTRAL AND DISTRIBUTED HEAT PUMP STRATEGY
AT VARIOUS DEMAND DENSITIES**

SEATTLE WEATHER PATTERN SPACE HEATING AND HOT DOMESTIC WATER SERVICE

COMPARISON OF CENTRAL AND DISTRIBUTED HEAT PUMP STRATEGIES

2944 "USERS" PER SQ. MI. SPACE HEATING SERVICE ONLY

**COMPARISON OF CENTRAL AND DISTRIBUTED HEAT PUMP STRATEGIES
SPACE HEATING AND HOT DOMESTIC WATER SERVICE
FOR 2944 "USERS" PER SQ. MI.**

**COMPARISON OF CENTRAL AND DISTRIBUTED HEAT PUMP STRATEGIES
SPACE HEATING HOT DOMESTIC WATER
AND SPACE COOLING SERVICE FOR 2944 "USERS" PER SQ. MI.**

For a given city, the choice between a central and a distributed HP-ICES strategy should be based upon a comparison of the best features of each strategy. The central strategy shows the best economic criteria for the space heat and domestic hot water option, while the distributed strategy shows the best criteria for the all-service option. These two cases are compared in Figure 4-5. Of the five cities chosen, only San Diego has a great enough cooling demand to cause this added feature in the distributed strategy to result in better economic criteria.

**COMPARISON OF CENTRAL STRATEGY PROVIDING SPACE HEATING
AND HOT DOMESTIC WATER
TO DISTRIBUTED STRATEGY PROVIDING SPACE HEATING, SPACE COOLING,
AND HOT DOMESTIC WATER**

5.0 EXPECTED ENVIRONMENTAL IMPACTS

Environmental considerations are divided into four phases of the system life: normal operation, failure mode operation, system construction phase, and eventual system retirement and disposal.

NORMAL OPERATION

The primary environmental effect of the system will be a beneficial reduction in both thermal pollution and atmospheric pollution from existing waste heat sources. Differences between central and distributed heat pump layouts are a matter of degree.

The decrease in thermal pollution arises from extracting energy from the waste stream "source". In many areas of the county, increased water body temperatures are resulting in eutrophication or are modifying the habits of migratory water fowl. A decrease in the waste energy input to these water bodies is very desirable.

A second decrease in thermal pollution arises from the improved efficiency by which fossil fuel is burned. The average efficiency of home heating burners is estimated in the range of 50 to 67 percent by various investigators. Larger fuel burning installations achieve much better efficiencies through reduced surface-to-volume ratios and through regular attention to maintenance procedures.

Decreased atmospheric pollution is predicted from the net fuel savings predicted for system operation. A secondary effect arises from the displacement of the location where fuel is burned and perhaps a shift in the type of fuel burned. Eliminating a host of individually fired heating units and replacing them with a heat pump system still requires the burning of fuel to generate electricity required for the heat pump compressor, but the fuel is burned in a remote power generation station rather than in the city core. Comparing the case where oil burners may be replaced by a heat pump system ultimately receiving power from an oil fired generating plant, lower atmospheric pollution will occur since sulfur and flyash scrubbing devices are used in the design of the generating plant stack, while an attempt to apply scrubbers to each of the home burners would be a prohibitive expense. The effect is less obvious when considering that some of the replaced units will undoubtedly have been gas fired and that the generating plant can use higher sulfur fuel, or fuel scarcity may require a shift to coal on the part of the generating station. For this situation, decreased atmospheric pollution will occur for the residential area, even if the overall load of pollutants borne by the atmosphere is unchanged.

The operation of waste heat supplied heat pumps will also reduce the peak power levels within existing electrical grids when replacing electrical resistance heating or air source heat pumps, thus reducing the operation of polluting peaking generators. Typical heat pumps operate at COP's approaching unity as temperatures drop thus maximizing power loads. Waste heat coupled heat pumps can maintain relatively constant COP's thus significantly reducing peak levels (and need for combustion devices such as gas turbines, etc.) and air pollution.

Noise pollution must also be considered prior to placement of air source heat pump units. Existing air-to-air heat pumps are relatively noisy by their very nature since, due to the thermodynamics involved, they must move large amounts of air. EPA recommendations and the current regulations in many cities require that nighttime residential noise levels be kept below 45 dba. No currently manufactured air source heat pump (nor any heat pump planned for production by at least seven of the major national manufacturers) can meet the 45-dba requirements if they are within 30 feet of the property. For many residential lots, there are no suitable locations that far away from the property line. Either central or distributed heat pump strategy, when replacing air source heat pumps, would effect a decrease in noise level as neither would require heat exchange with the outside air.

The subject of visual aesthetics of above ground installations deserves mention under normal operation. It is assumed that most of the equipment will be located underground. The topping system will probably be an above ground facility; however, designing this structure in harmony with surrounding architectural styles will avoid citizen resistance to the project.

POLLUTION CONSIDERATIONS IN FAILURE MODE

Two primary considerations for failure mode pollution are refrigerant leaks from the heat pump systems and water leaks from the distribution system. These considerations differ for the central and distributed configurations.

It is very likely that regular maintenance and inspection procedures will identify refrigerant leakage in the central configuration before a significant amount has escaped (barring catastrophic failures during earthquakes, etc.). In any event, both the amount of and the human exposure to refrigerant leaks may be minimized through appropriate monitoring for the central layout. For the distributed case, the degree of maintenance and inspection which is expected is inversely proportional to the system size. Thus small units installed in single family residences may receive minimal maintenance, perhaps limited to annual filter changes, whereas the management of multiple residence complexes will likely provide at least bi-annual checkout (upon change from heating to cooling mode and vice versa). A parallel situation exists when considering existing home and commercial refrigeration equipment. Similar maintenance is expected; units are widespread; but actual escape of fluorocarbon refrigerants to the atmosphere is more due to the common practice of venting the refrigerant to the atmosphere during service work (and the use of aerosol propellants) than to system leaks. Incorporation of a cold trap (liquid nitrogen) at the vacuum pump exhaust for refrigeration servicemen will significantly reduce the total fluorocarbon released to the atmosphere.

Leakage of water from the distributing system presents a pollution problem only from whatever dissolved materials may be carried by the water. For the central heat pump configuration, it is likely that water quality will be maintained high with fouling and corrosion inhibitors in trace amounts being the only solutes. As this is a closed system with water essentially conserved (makeup for leakage) investment in corrosion inhibiting and antifoulants is a first cost item. A leakage condition in the distributing system will be readily apparent and repaired promptly.

6.0 PROJECTED GROWTH

Generally, HP-ICES will be most cost competitive with conventional heating and/or cooling systems in areas of high demand density, i.e., urban areas and major residential areas. Most likely, the most advantageous systems (cheapest and most readily accessible energy sources closely coupled to energy demands) will be implemented first. Such a system could well be a self-contained source-demand situation as is sometimes found within small industrial parks, individual shopping centers or large apartment complexes. Alternately, a particularly attractive waste energy stream may be applied to a nearby high demand density urban area. In either case, by the addition of energy storage modules, approaching true annual energy storage systems, the service area can perhaps be expanded. The growth of these areas is often controlled by city planners through zoning regulations. Gradual relaxation of zoning restrictions, allowing progressively higher population density and occasional change from commercial to industrial activity, are the most likely changes to which the HP-ICES must adapt.

During the planning phase of any HP-ICES, city planners will be consulted concerning their long-range objectives and the design evolved to accommodate foreseen changes within the service area. Thus, oversize trunk piping may be indicated in some areas to allow expansion of the service area into selected nearby regions, which at the outset are too sparsely populated to warrant investment in distribution piping.

The increase in population density represents the potential need for increased energy supplied by the HP-ICES. Increased capacity can be provided by adding heat pump modules and/or additional waste heat sources. The likelihood is that both water flow rate and sending temperature would be increased, although the tradeoff would require analysis under each specific situation, to achieve the desired energy delivery with the minimum expenditure.

For HP-ICES strategies offering both heating and cooling, the shift from lower energy density towards higher energy density demand also shifts the ratio of cooling to heating. The higher demand structures tend to require core cooling and perimeter heating simultaneously during at least a portion of the year. The cooling demand for these structures will result in an increased energy available for heating elsewhere in the system. To make optimum use of this effect will require very detailed planning in the early stages for specific applications.

For the distributed heat pump case, an increase in the energy supplied from an unchanged waste energy supply requires an increased temperature difference across the distribution network. Hence, an adjustment would be required in all the existing heat pumps, causing them to operate somewhat off their design optimum. This effect may well be slight in systems where the temperature difference in the distribution network is small, however, for systems with large temperature differences, the effect may be prohibitive.

The European expansion technique for straight district heat systems, i.e., providing mobile fossil fuel-fired boilers which are temporarily incorporated into the distribution system, may serve as a solution for this case until additional industrial waste energy becomes available. Another potential solution would be to incorporate a centralized heat pump to lift residual energy from the return line to the supply line, increasing the supply line temperature, and thus decreasing the water flow requirement for each existing user. Such a device would only be necessary during peak demand modes, and, thus, could potentially represent a very cost-effective approach.

In either the central or the distributed configuration, increased water flow through the piping network can be accommodated through increased pumping capacity and parasitic power. The parasitic power, due to the water pumps, currently forms a small fraction of the total parasitic power, and, thus, pumping power can be increased significantly without excessive effect upon the overall system.

The incorporation of additional waste energy sources, as such become available, should be possible with no severe disturbance to the operation of the existing system and without cessation of service to existing customers. As commercial property is rezoned to allow industrial activity within the service area of an HP-ICES, the effects will be to increase the supply of waste energy and perhaps to decrease the demand. Both effects will encourage system expansion.

Finally, the effect of the existence of an integrated community energy system, with its potential of supplying less expensive energy, upon the growth of the community deserves mention. Assuming that the system realizes its potential, the effect will be to induce potential customers to locate within the service area. Similarly, any incentives arranged to encourage existing industries to furnish their waste energy to the ICES will also act to attract further appropriate industries to the service area. These incentives can include:

1. Preferential treatment in fuel supply shortages.
2. Elimination or reduction of capital expenditures for cooling towers
3. Payment for waste energy
4. Rapid siting approval

By appropriate attention to these incentives in the planning stages, an appropriate climate for system growth can be created.

7.0 IDENTIFIED VARIATIONS

Two determinants which strongly influence the economic competitiveness of the heat pump assisted integrated community energy system are the population density in the vicinity of the heat source and the characteristics of the annual energy demand.

Greater population density acts to increase the demand density for energy, hence a given amount of the product can be supplied with lower investment in distribution piping. This improves the cost competitiveness of the ICES over conventional heating/cooling means, as well as influencing the tradeoffs between centrally located heat pump designs and those incorporating distributed ones. The second influential factor involves the nature of the energy demand. Basically, heating demand increases from near negligible in the southern tip of Florida, to very substantial (over 10,000 degree-days/year) in the extreme northern central area of the U.S., as shown in Figure 7-1. Comfort cooling demand decreases from near negligible (less than 500 degree-days/year) in the Pacific Northwest and mountain regions, to over 4,500 degree-days/year in southern Florida, as shown in Figure 7-2, while the demand to heat potable water is relatively constant geographically and equivalent to a 2,000 degree-day space heating demand. The total demands for space heating, space cooling, and hot water production varies from approximately 7,000-degree days in the south and Pacific Northwest to nearly 13,000 degree days equivalent in the extreme north central.

These demands must be modified to some extent as a function of demand density, as the higher demand density regions are influenced to a greater extent by energy dissipation within the structures. Thus, regions showing low demand for space cooling in Figure 7-2 may in truth have significant demand for space cooling in the more densely populated or commercial neighborhoods. Similarly, high density neighborhoods in national regions which show moderate space heating demand may in actuality require little or no space heating and more space cooling than indicated in Figure 7-2.

A survey study, such as the one herein reported, must retain sufficient generality in preliminary phases to avoid eliminating potentially attractive situations through over specification. Three generalized combinations of energy demands can be identified, and relationships between various design parameters discussed. These three combinations are two end points of the heat cooling spectrum and the mid-point.

In regions where space cooling demand dominates the annual requirements for energy, it is possible that the most cost-effective central system would provide chilled water only, with the heating and hot water functions supplied by alternate means. The distributed system could provide hot water from the heat liberated in the condenser, and the small heating load during the winter from the reversed refrigeration mode of the heat pump. For very high demand density, the additional expense to provide space and hot water heating from the central system may be warranted. For lower demand densities, the distributed system may be indicated.

HEATING DEGREE-DAY DISTRIBUTION ACROSS THE UNITED STATES

SOURCE: STROCK AND KORAL (1965)

29016-83

Figure 7-1

COOLING DEGREE-DAY DISTRIBUTION ACROSS THE UNITED STATES

AVERAGE ANNUAL TOTAL NUMBER OF COOLING DEGREE DAYS

SOURCE: STROCK AND KORAL (1965)

29016-84

Figure 7-2

In regions where neither the space heating nor the space cooling demand dominates the annual energy requirement, there is little change in the design of the distributed system; however, the central system may show distinct advantages when an absorption cooler is provided at the user sites and the distribution system arranged to provide hot water the year around.

In regions where the space heating demand dominates the energy demand, designs are the most straightforward. Both central and distributed heat pump arrangements operate with the pipe systems. Here the economy of scale of a central heat pump facility appears to dominate the versatility advantages of the distributed systems. This is the baseline situation currently modeled from analytical studies.

A host of other parameters exist, to which a specific HP-ICES may be tailored. These are approached on a site-by-site basis; however, some general notes concerning their influence may be stated.

Systems which utilize highly cyclical waste energy streams will tend to show better economic criteria when significant storage capability is included in the design. The optimum location of this storage is not yet clear.

Systems which are characterized by large variation between peak demand and average demand will tend to show the best economic performance with storage located as close to the user as possible. This strategy minimizes the length of main line which must be designed to carry the peak energy demand. There is some indication that increased topping (i.e., a higher percentage of the annual energy demand per user) may also be indicated. This may result in extension of the system into somewhat lower demand density areas, as the waste energy source is capable of supplying more users under these conditions.

Special problems in piping installation are foreseen from elevation changes in the terrain within the supply area, composition of the soil in which the system is to be buried (i.e., bedrock outcroppings), and prior location of other utility lines (i.e., subways, storm and sanitary sewers, electric and telephone cables, potable and fire control water piping, and gas lines). The most likely system tailoring response to these situations would be in the location and required length of piping.

The nature of an available waste energy stream will, also, elicit appropriate design responses. Thus, a gaseous waste energy stream may favor a centralized heat pump over a distributed system, all else being equal, as an additional expense over the baseline distributed heat pump system will be required for the gas-to-water heat exchanger, while the central heat pump design would change only in detail.

Another variation comes from the potential to supply heat to the system from more than one waste energy source. Several advantages foreseen from this variation are: 1) decreased reliability (or decreased dependence on backup systems) through decreased probability that all sources will fail simultaneously, 2) decreased expenditure for mains piping as, for a given transmission distance, all the energy need not be transmitted through a single pipe, and 3) smoothed availability with time.

The existence of plans for industrial parks or redevelopment/reconstruction effort presents another special case to which an HP-ICES may be tailored. Under these situations, essentially no disadvantages are foreseen associated with abandonment of functional HVAC equipment or piecemeal system hookup, as existing equipment becomes obsolete.

8.0 SPECIFIC SITE ANALYSES

The generalized tradeoff studies presented in Section 1.0 are necessarily performed based upon equal service from systems with central and distributed strategies. Thus, the comparisons cannot be made between the best design options for each of the two strategies, for there is no basis for comparison of strategies which provide different services. For a specific site, however, the relative importance of different service options is inherently defined by climatological considerations; thus the best features of the central strategy can be brought out through comparisons with other central strategy design options, the best features of the distributed strategy similarly emphasized and the final strategy choice made based upon a comparison of the two internally optimized systems. Whereas the generalized strategy comparisons can serve as guidelines, the final strategy choice for any specific site should be based upon a comparison of best performing central and distributed strategies.

Three specific sites have been chosen to serve as examples of this process. The primary site, in Everett, Washington, has been chosen as particularly attractive from a waste energy availability standpoint. At this site, the energy currently dissipated in the warm water outfall from a large paper mill can be lifted with heat pumps and supplied to the commercial business core area and surrounding residential area. The second site chosen consists of an aggregation of commercial and industrial enterprises in the southern portion of Seattle, Washington, coupled to the surrounding residential districts. This site has nearly identical weather patterns to the first site, but different energy availability and residential-density effects. A small-scale first step for this overall system received particular attention. A somewhat similar site exists in the northwestern suburbs of San Antonio, Texas, and was selected for the third example site with a significantly different weather pattern. A number of assumptions have been made regarding specific similarities of the second and third sites, so that the effect of weather pattern difference will be as unclouded as possible. In the following paragraphs, additional details of these sites, descriptions of the indicated HP-ICES systems and performance predictions for these sites are presented.

EVERETT, WASHINGTON

Community Description

The first site studied is located in the City of Everett, Washington, 29 miles north of Seattle. Everett is situated on a peninsula formed by the Snohomish River to the east and north, and Puget Sound on the west, with a mean elevation of 99 feet above sea level. Terrain is level and rolling, subsoil is glacial till. Annual average weather characteristics are very similar to Seattle, with mean heating seasons equal to 2-1/2 percent accuracy, mean temperature, average daily high and low temperatures all equal to those of Seattle within 1/2 degree Fahrenheit.

The population of Everett has shown a steady increase over the last several decades, stands at 59,000 (1970 census), and is predicted to reach 88,000 by 1985. Approximately 60 percent of this

population resides in the 10 census tracts surrounding the downtown business core, as shown in Figure 8-1. Housing density is developed from 1970 census data in Table 8-1. The Everett area is a mature urban area undergoing gradual, planned development to meet the needs of a growing influx of younger persons. The most common structure is an older, single family residence of frame construction. Nearly 60 percent of the housing units in this area were constructed before 1939 and three quarters before 1949. A large fraction of the counties elderly population resides in this area, and most are long-term residents.

Table 8-1
HOUSING DENSITY
EVERETT, WASHINGTON

Tract No.	Area	Total Housing Units	Density HU/mi ²	Percent Multiple
401	1.86	1,771	952	8
402	1.28	1,360	1,062	30
403	0.42	1,291	3,103	2
404	0.77	1,842	2,398	28
405	0.80	912	1,140	3
406	0.78	594	761	21
407	0.37	1,393	3,764	44
408	0.61	1,161	1,903	42
409	0.96	911	917	12
410	0.61	1,924	3,164	14

The growth of local industry (aerospace, paper, and lumber products) is attracting younger persons to the area. The mean number of households is increasing more rapidly than the population through a trend toward smaller families. The resulting market for more, smaller housing units is being met through gradual relaxation of zoning restriction, especially in the regions surrounding the downtown business core.

Heating system data for the residential structures is compiled in Table 8-2. No particular heating system type is prevalent. There is a trend toward conversion of older systems to electric baseboard heaters. This heating system is locally both the lowest initial cost and the lowest energy charge system available.

The estimated aggregate floor space for commercial and light industrial activity in the city of Everett is 8.5 million square feet. There are 3,392 establishments (2,500 ft² average), with an aggregate energy demand of $1,431 \times 10^7$ Btu/year for space heating and hot potable water production. Approximately 30 percent of this activity is concentrated in the business core district, yielding an estimated energy demand, in addition to the residential demand, of 432×10^9 Btu/year. Due to the small average size predicted, this energy demand is most easily combined with that of

**CITY OF EVERETT
ZONING DETAIL**

BUSINESS CORE

**HIGH DENSITY
RESIDENTIAL (R4 & R5)**

the residential housing by defining the number of housing units which would have an equivalent demand on an annual basis. As the annual demand of a housing unit aggregated to 6.9×10^7 Btu/year, the business core commercial demand equates to 6.260 housing units.

Table 8-2
HEATING SYSTEM DATA
EVERETT, WASHINGTON

Census Tract No.	Total Housing Units	Stream or Hot Water	Central Forced Air	Electric Baseboard	Other (Includes Unheated Structures)	Air Conditioned (Percent)
401	1,771	187	806	467	301	2
402	1,360	5	300	507	548	2
403	1,291	9	452	373	457	3
404	1,842	285	405	600	552	2
405	912	23	163	308	418	—
406	594	50	117	107	320	2
407	1,393	356	251	401	385	—
408	1,161	365	223	317	256	3
409	911	44	381	396	90	10
410	1,924	228	630	574	492	3

The business core zone is distributed 5 percent in census tract 404, 50 percent in census tract 407, and 45 percent in census tract 408. Table 8-3 presents total demand (represented by equivalent housing units), and specific demand (represented by equivalent housing units per square mile) for these three census tracts.

Table 8-3
COMBINED RESIDENTIAL AND COMMERCIAL DEMAND FOR BUSINESS CORE

Census Tract No.	Area (Square Miles)	Residential Housing Units	Equivalent Housing Units Commercial	Total Housing Units	Density HU/mi ²
404	0.77	1,842	313	2,155	2,798
407	0.37	1,393	3,130	4,423	11,950
408	0.61	1,161	2,817	3,978	6,521

Some error will be introduced through this treatment; however, the sensitivity of demand to ambient temperature should be reasonably well modeled. As the calculation procedure averages demand over each day, no additional inaccuracy in diurnal pattern mismatch will be incurred to the extent that commercial operators set back their heating system controls during nonbusiness days (i.e. weekends).

A large pulp and paper mill is located at the north end of the waterfront of census tract 404. This plant maintains four waste-water outfall lines to Puget Sound, with a combined flow rate of 52.6 million gallons per day, at a mean (winter average) temperature of 68.3°F. Assuming a mean coefficient of performance of 3, this source can supply the peak instantaneous demand of 1,260 homes or the 99.6 percent demands of 1,610 homes (based upon the test reference year weather data) for each degree decrease in the source temperature.

The plant operates 24 hours per day, 358 to 360 days per year, with major maintenance scheduled during the scattered 5 to 7 nonoperating days. Stream flow variations are minimal as the pollution control units upstream (settlers and clarifiers) act to damp out variations in the process flows.

System Description and Growth Plan

A search was made for the most cost-competitive combination of system design variables, as well as heat pump location strategy. Other design options investigated were service furnished, overall system size, equivalent number of residences, sending temperature, return temperature, size of thermal storage system, and heat pump capacity. The most cost-competitive HP-ICES system for this site is a central strategy, providing for the demands of space heating and domestic hot water heating. The system provides these demands to an equivalent of 15,131 housing units, composed of approximately 60 percent residential and 40 percent small commercial customers. A three-step implementation plan is identified.

In the first step, census tracts 407 and 408 are supplied by the system. Demand for these tracts is approximately 30 percent residential and 70 percent commercial. Over 40 percent of the residential demand is from multiple housing (five or more units per structure). Advantages foreseen from taking this area in the first step are:

1. This area has the highest demand density, hence the lowest specific cost of distribution network, and most favorable payback criteria.
2. This area has the densest commercial activity.

It is believed that the operators of a commercial establishment will be more receptive to the technical advantages of the district heating system, whereas owners of single family residences may be less easily convinced technically, i.e., more prone to intangible doubts.

In the second step, the system is expanded to the North and South to incorporate census tracts 404 and 410, which contain a substantial fraction of the high density residential zoning. The equivalent demand density of the second step, at 2,964 HU/mi² (housing units per square mile) is significantly lower than that of the first step (at 8,607 HU/mi²).

In the third and final step, the system is expanded northwest onto census tracts 403 and 402. The demand density of the third step at 1,563 HU/mi² is currently expected to increase due to the substantial area zoned R-4 in census tract 402.

Optimizations of heat pump capacity, system supply temperature, return temperature, and storage size were performed for the final (15,131 housing unit) case. A final heat pump capacity of 14,500 tons is required, 8,000 tons at the first step, 4,000 tons added during the second step, and 2,500 tons added during the final step. System supply (160°F) and return (75°F) temperatures follow the optimization for the primary site.

Approximately 4,000 feet of main pipeline is required between the heat pump location and the first branch into submains. A tentative layout of mains and submains is provided as Figure 8-2. No attempt has been made in this layout to correlate with the location of existing sewer mains or to match timing with severe renovation project.

HP-ICES Performance at Everett Site

The system provides space heating and domestic hot water demand for the equivalent of 15,131 housing units, distributed approximately 60 percent to residential and 40 percent to commercial customers. The calculation routine used to estimate system performance is included as Appendix A. Briefly summarized, the demand is estimated from historical dry bulb temperature records day by day through a reference year and cumulated. System parasitic power, topping energy, thermal loss, and energy withdrawn from waste heat streams are similarly cumulated to annual totals.

Representative performance of the HP-ICES is diagrammed in Figure 8-3 as the annual total energy flow. Figure 8-4 presents the corresponding data for a conventional system providing the same service. The efficiency for the HP-ICES is calculated as the ratio of the total useful service provided to the total fuel input required. Energy withdrawn from the waste energy "source", since it would be dissipated to the environment in the absence of the HP-ICES, is not considered as an input for efficiency calculations. The representative first law efficiency for the HP-ICES, at 86.5 percent, is nearly double that of the conventional system at 45.5 percent. Analysis from the standpoint of the second law of thermodynamics yields representative operation energy flow diagnosis for the HP-ICES and the conventional system as presented in Figures 8-5 and 8-6, respectively. The work-producing potential of the energy withdrawn from the source is a very small fraction of the total, but has been included in the computation of second law efficiencies. The HP-ICES second law efficiency, at 7.38 percent is also nearly double that of the conventional system (3.97 percent).

Peak mode operation is shown as hourly energy flow on that day where demand was highest. The first law energy balance of the HP-ICES is diagrammed in Figure 8-7. The comparable case for the conventional system is Figure 8-8. The HP-ICES first law efficiency in peak mode is 86.7 percent, over 1-1/2 times the 53.1 percent figure for the conventional system. The second law of thermodynamics analysis yields the diagrams of Figures 8-9 and 8-10, for HP-ICES and conventional systems, respectively. Overall efficiencies on a second law basis are 4.99 percent (HP-ICES) and 3.12 percent (conventional).

ENERGY FLOW DIAGRAM
HP-ICES
EVERETT SITE
REPRESENTATIVE OPERATION

UNITS: 10^{10} Btu/YEAR

**ENERGY FLOW DIAGRAM
CONVENTIONAL SYSTEM
EVERETT SITE
REPRESENTATIVE OPERATION (ANNUAL TOTAL)**

UNITS: 10^{10} Btu/yr

AVAILABILITY DIAGRAM
HP-ICES
EVERETT SITE
REPRESENTATIVE OPERATION

UNITS: 10^{10} Btu/YEAR
REFERENCE SINK 50°F

**AVAILABILITY DIAGRAM
CONVENTIONAL SYSTEM
EVERETT SITE
REPRESENTATIVE OPERATION**

UNITS: 10^{10} Btu/YEAR
REFERENCE SINK 50°F

ENERGY FLOW DIAGRAM
HP-ICES
EVERETT SITE
PEAK OPERATION

UNITS: 10^6 Btu/HR

**ENERGY FLOW DIAGRAM
CONVENTIONAL ALTERNATE SYSTEM
EVERETT SITE
PEAK DEMAND**

UNITS: 10^6 Btu/hr

AVAILABILITY DIAGRAM
HP-ICES
EVERETT SITE
PEAK OPERATION

UNITS: 10^6 Btu/HR
REFERENCE SINK 50°F

**AVAILABILITY DIAGRAM
CONVENTIONAL SYSTEM
EVERETT SITE
PEAK OPERATION**

**UNITS 10^6 Btu/HOUR
REFERENCE SINK 50°F**

Economic Analysis, Everett Site

The cost of major system elements estimated from component sizes defined in the tradeoff studies is presented in Table 8-4. These costs are cumulated to a system total cost and the percentage contribution of each item calculated. The life cycle cost analysis for the full system is presented as Table 8-5. A comparable life cycle cost analysis for a conventional system is presented as Table 8-6. The most influential assumption in the economic analysis is the annual increase in the price of fuel. A sensitivity analysis against fuel escalation rate was performed. The variation in system net present value and first year net are presented as a function of the annual increase in the real cost of energy in Figure 8-11. The system shows profitability even at low energy escalation rates. Figure 8-12 shows the variation of the system internal rate of return with energy escalation rate. System profitability is again shown, as the internal rate of return exceeds the cost of capital, even for low energy escalation rates.

Table 8-4
COST OF MAJOR SYSTEM ELEMENTS
EVERETT SITE

Element	Cost	Percentage
Central heat pumps	5,189,000	12
Storage tanks	0	0
Distribution system	34,238,000	77
Topping/backup boiler	933,000	2
Central cooling tower	0	0
User devices	4,910,000	8
Transmission pipeline	420,000	1
Total hardware cost	45,690,000	100
Contingency	6,912,000	
Estimated cost	52,602,000	
Inflation, 7 years at 5% per year	21,418,000	
Estimated cost (1985)	74,020,000	

A search of applicable codes, statutes, regulations and ordinances was made to identify any barriers to the implementation of HP-ICES concepts in general. A specific search of applicable codes, statutes, regulations and ordinances was made for the Everett site. No unsurmountable barriers were identified in either search. Rather, certain situations exist which will require attention during design and implementation of these systems.

Central System (Everett Site)

Table 8-5

ECONOMIC ANALYSIS
VERSION 2.0

ASSUMPTIONS

CURRENT ENERGY COSTS (BASE DOLLARS)

USED ENERGY COST (\$/10E6BTU) 3.571 (CONSUMED AT .60 EFFICIENCY)

FOSSIL TOPPING COST (\$/GAL) .4000 (NO. FUEL OIL CONSUMED AT 0.85 EFFICIENCY)

PUMP AND FAN ENERGY COST (\$/KW-HR) .0400

PLANT LIFE (YEARS) 30.00 (START OF PLANT OPERATION - 1985)

AFTER TAX COST OF CAPITAL .0800

ESCALATION RATES

GENERAL INFLATION RATE/YEAR .0500

LABOR ESCALATION RATE/YEAR .0600

FOSSIL ENERGY ESCALATION RATE/YEAR .1340

ELECTRICAL ESCALATION RATE/YEAR .1140

SPACE HEATING DEMANDS SUPPLIED (BTU/YEAR) .71106E+12

HOT WATER DEMANDS SUPPLIED (BTU/YEAR) .20367E+12

SPACE COOLING DEMANDS SUPPLIED (BTU/YEAR) 0.

NET PRESENT VALUE AT 0.08 = .5669E+09

INTERNAL RATE OF RETURN = .2787

TOTAL SYSTEM COST (\$1985) AT START OF SYSTEM OPERATION .7402E+09

CONVENTIONAL ALTERNATE SYSTEM COST .2947E+09

YEAR	SALES	CAP. COSTS	OPERATION	FUEL	ELECTRIC	LOAN INT	NET	LOANS	PV AT .08
1985	.2343E+08	.6779E+07	.1491E+07	.3304E+05	.8457E+07	0.	.6667E+07	0.	.6173E+07
1986	.2573E+08	.6779E+07	.1573E+07	.3747E+05	.9421E+07	0.	.7923E+07	0.	.6793E+07
1987	.2833E+08	.6779E+07	.1654E+07	.4244E+05	.1049E+08	0.	.9350E+07	0.	.7423E+07
1988	.3124E+08	.6779E+07	.1751E+07	.4814E+05	.1169E+08	0.	.1097E+08	0.	.8065E+07
1989	.3452E+08	.6779E+07	.1847E+07	.5464E+05	.1302E+08	0.	.1281E+08	0.	.8722E+07
1990	.3821E+08	.6779E+07	.1944E+07	.6194E+05	.1451E+08	0.	.1491E+08	0.	.9395E+07
1991	.4235E+08	.6779E+07	.2056E+07	.7027E+05	.1616E+08	0.	.1729E+08	0.	.1009E+08
1992	.4702E+08	.6779E+07	.2169E+07	.7968E+05	.1801E+08	0.	.1999E+08	0.	.1080E+08
1993	.5227E+08	.6779E+07	.2284E+07	.9036E+05	.2006E+08	0.	.2305E+08	0.	.1153E+08
1994	.5814E+08	.6779E+07	.2414E+07	.1025E+06	.2234E+08	0.	.2656E+08	0.	.1229E+08
1995	.6459E+08	.6779E+07	.2547E+07	.1162E+06	.2489E+08	0.	.3326E+08	0.	.1426E+08
1996	.7508E+08	.6779E+07	.2687E+07	.1314E+06	.2773E+08	0.	.3775E+08	0.	.1499E+08
1997	.8351E+08	.6779E+07	.2834E+07	.1494E+06	.3089E+08	0.	.4285E+08	0.	.1574E+08
1998	.9300E+08	.6779E+07	.2991E+07	.1695E+06	.3441E+08	0.	.4865E+08	0.	.1656E+08
1999	.1037E+09	.6779E+07	.3155E+07	.1922E+06	.3834E+08	0.	.5523E+08	0.	.1741E+08
2000	.1157E+09	.7700E+07	.4313E+07	.2179E+06	.4271E+08	0.	.6079E+08	0.	.1774E+08
2001	.1293E+09	.7700E+07	.4550E+07	.2471E+06	.4757E+08	0.	.6922E+08	0.	.1871E+08
2002	.1446E+09	.7700E+07	.4800E+07	.2802E+06	.5300E+08	0.	.7879E+08	0.	.1972E+08
2003	.1618E+09	.7700E+07	.5064E+07	.3178E+06	.5904E+08	0.	.8966E+08	0.	.2078E+08
2004	.1812E+09	.7700E+07	.5342E+07	.3604E+06	.6577E+08	0.	.1020E+09	0.	.2189E+08
2005	.2075E+09	.7700E+07	.5636E+07	.4086E+06	.7327E+08	0.	.1205E+09	0.	.2394E+08
2006	.2322E+09	.7700E+07	.5946E+07	.4634E+06	.8162E+08	0.	.1365E+09	0.	.2510E+08
2007	.2600E+09	.7700E+07	.6273E+07	.5255E+06	.9092E+08	0.	.1545E+09	0.	.2632E+08
2008	.2913E+09	.7700E+07	.6614E+07	.5955E+06	.1013E+09	0.	.1751E+09	0.	.2761E+08
2009	.3266E+09	.7700E+07	.6982E+07	.6754E+06	.1128E+09	0.	.1984E+09	0.	.2897E+08
2010	.3664E+09	.7700E+07	.7386E+07	.7663E+06	.1257E+09	0.	.2244E+09	0.	.3040E+08
2011	.4112E+09	.7700E+07	.7772E+07	.8690E+06	.1400E+09	0.	.2544E+09	0.	.3191E+08
2012	.4619E+09	.7700E+07	.8154E+07	.9854E+06	.1560E+09	0.	.2890E+09	0.	.3350E+08
2013	.5189E+09	.7700E+07	.8550E+07	.1117E+07	.1738E+09	0.	.3277E+09	0.	.3517E+08
2014	.5833E+09	.7700E+07	.8976E+07	.1267E+07	.1936E+09	0.	.3717E+09	0.	.3693E+08

Conventional Alternate System (Everett Site)
Economic Analysis
VEESTON 2.0

Table 8-6

ASSUMPTIONS

CURRENT ENERGY COSTS (BASE DOLLARS)
USER ENERGY COST (\$/1000 BTU) .3571 (CONSUMED AT .60 EFFICIENCY)
FOSSIL TOPPING COST (\$/GAL) .4000 (NO. FUEL OIL CONSUMED AT 0.95 EFFICIENCY)
PUMP AND FAN ENERGY COST (\$/KW-HR) .0000

PLANT LIFE (YEARS) 30.00 (START OF PLANT OPERATION = 1985)

AFTER TAX COST OF CAPITAL .0800

ESCALATION RATES

GENERAL INFLATION RATE/YEAR .0500
LABOR ESCALATION RATE/YEAR .0600
FOSSIL ENERGY ESCALATION RATE/YEAR .1300
ELECTRICAL ESCALATION RATE/YEAR .1100

SPACE HEATING DEMANDS SUPPLIED (BTU/YEAR) .7110E+12
HOT WATER DEMANDS SUPPLIED (BTU/YEAR) .4000E+12
SPACE COOLING DEMANDS SUPPLIED (BTU/YEAR) .1000E+11

NET PRESENT VALUE AT 0.08 = 0.
INTERNAL RATE OF RETURN = .0000E+01

TOTAL SYSTEM COST (\$1000) AT START OF SYSTEM OPERATION .4735E+08

CONVENTIONAL ALTERNATE SYSTEM COST .4735E+08

YEAR	SALES	CHG. COSTS	DEPRECIATION	FUEL	ELECTRIC	LOAN INT.	NET	LOANS	PV AT .08
1985	.2840E+08	.7057E+07	.2413E+07	.1021E+08	.7427E+07	0.	0.	0.	0.
1986	.2857E+08	.7057E+07	.2413E+07	.1157E+08	.8719E+07	0.	0.	0.	0.
1987	.2873E+08	.7057E+07	.2413E+07	.1313E+08	.9713E+07	0.	0.	0.	0.
1988	.2889E+08	.7057E+07	.2413E+07	.1488E+08	.1042E+08	0.	0.	0.	0.
1989	.2905E+08	.7057E+07	.2413E+07	.1688E+08	.1200E+08	0.	0.	0.	0.
1990	.2921E+08	.7057E+07	.2413E+07	.1914E+08	.1343E+08	0.	0.	0.	0.
1991	.2937E+08	.7057E+07	.2413E+07	.2171E+08	.1458E+08	0.	0.	0.	0.
1992	.2953E+08	.7057E+07	.2413E+07	.2461E+08	.1558E+08	0.	0.	0.	0.
1993	.2969E+08	.7057E+07	.2413E+07	.2781E+08	.1658E+08	0.	0.	0.	0.
1994	.2985E+08	.7057E+07	.2413E+07	.3135E+08	.1758E+08	0.	0.	0.	0.
1995	.3001E+08	.7057E+07	.2413E+07	.3524E+08	.1858E+08	0.	0.	0.	0.
1996	.3017E+08	.7057E+07	.2413E+07	.3947E+08	.1958E+08	0.	0.	0.	0.
1997	.3033E+08	.7057E+07	.2413E+07	.4407E+08	.2058E+08	0.	0.	0.	0.
1998	.3049E+08	.7057E+07	.2413E+07	.4907E+08	.2158E+08	0.	0.	0.	0.
1999	.3065E+08	.7057E+07	.2413E+07	.5447E+08	.2258E+08	0.	0.	0.	0.
2000	.3081E+08	.7057E+07	.2413E+07	.6027E+08	.2358E+08	0.	0.	0.	0.
2001	.3097E+08	.7057E+07	.2413E+07	.6647E+08	.2458E+08	0.	0.	0.	0.
2002	.3113E+08	.7057E+07	.2413E+07	.7307E+08	.2558E+08	0.	0.	0.	0.
2003	.3129E+08	.7057E+07	.2413E+07	.8007E+08	.2658E+08	0.	0.	0.	0.
2004	.3145E+08	.7057E+07	.2413E+07	.8747E+08	.2758E+08	0.	0.	0.	0.
2005	.3161E+08	.7057E+07	.2413E+07	.9527E+08	.2858E+08	0.	0.	0.	0.
2006	.3177E+08	.7057E+07	.2413E+07	.10347E+09	.2958E+08	0.	0.	0.	0.
2007	.3193E+08	.7057E+07	.2413E+07	.11217E+09	.3058E+08	0.	0.	0.	0.
2008	.3209E+08	.7057E+07	.2413E+07	.12147E+09	.3158E+08	0.	0.	0.	0.
2009	.3225E+08	.7057E+07	.2413E+07	.13137E+09	.3258E+08	0.	0.	0.	0.
2010	.3241E+08	.7057E+07	.2413E+07	.14187E+09	.3358E+08	0.	0.	0.	0.
2011	.3257E+08	.7057E+07	.2413E+07	.15297E+09	.3458E+08	0.	0.	0.	0.
2012	.3273E+08	.7057E+07	.2413E+07	.16467E+09	.3558E+08	0.	0.	0.	0.
2013	.3289E+08	.7057E+07	.2413E+07	.17707E+09	.3658E+08	0.	0.	0.	0.
2014	.3305E+08	.7057E+07	.2413E+07	.19017E+09	.3758E+08	0.	0.	0.	0.

**SENSITIVITY OF INTERNAL RATE OF RETURN
TO FUEL ESCALATION RATE**

GENERALIZED CONSIDERATIONS

DIVERSITY OF BUILDING CODES

It has been estimated that between 5,000 and 10,000 building codes exist. Four national organizations generate model codes on a study of the nature of the one herein reported, exhaustive search of such a body of material is not warranted. Each code has the potential of containing an awkward or forbidding clause, however, none were located by the several codes consulted. Usually codes contain statements to assure that sufficient thermal capacity will be available from the heating system in unusually cold weather, to avoid undue discomfort. In some cases, such statements could result in the requirement for oversized user devices. Either strategy would be penalized although the central strategy would suffer less, as the efficiency of the required heat exchanger tends to increase with overdesign. The overall efficiency of the distributed heat pump decreases with overdesign as a greater portion of the time is spent operating at part load. To mitigate the effect of code diversity, a careful study must be made of all locally applicable codes (several may apply) before committing to a project. Should these codes require oversized heating equipment, the system can still be implemented at somewhat reduced efficiency and economic benefit. An alternate approach would be to attempt to effect a change in the applicable code.

Public and political inertia works against change, perhaps especially so when the change can be viewed as exposing consumers (voters) to increased physical discomfort. A coordinated effort upon the part of the national regulatory bodies to insert beneficial statements regarding district heating equipment into the model codes, could be successful, eventually, in effecting similar changes in the various local codes.

CODE ENFORCEMENT AUTHORITY

Enforcing authorities for local codes are as varying as the codes themselves. Traditionally, assuring the soundness of the building structure has been the most important task of enforcement. Maintaining aesthetic values in the local region has become a significant task more recently. As a result, employees of enforcement authorities are unlikely to possess either the skill or the interest to approve novel heating systems.

In some cases, police departments, fire departments, city road maintenance officials and sewer departments may have the ability to effectively veto a project. These persons, too, may not possess the skill to properly assess the long-term benefits of a project against the obvious short-term disruption of the service under their jurisdiction. The proposer of an integrated community energy system would prudently include these lower level officials in his efforts to sell his concept to the community.

REAL ESTATE APPRAISAL PRACTICE

Predominant practice in the assessment of taxes upon real property owners applies a flat rate against the appraised value of the property. Ostensibly, a new, highly efficient, inexpensive to operate heating system will be perceived as an advantage to the appraiser as well as the subscriber. If not,

the subscriber will find it difficult to recover his investment when he sells his home; if so, his taxes increase and he loses some of the economic benefit of his investment. To mitigate this "Catch 22" situation, either: 1) special tax credits to subscribers could be enacted or 2) the system can be set up so that the ownership of the equipment rests with the utility. This latter option has additional advantages in that the maintenance of the equipment is under better control, giving better assurance that the system efficiency will remain high.

UTILITY REGULATION PRACTICE

Any community energy system which serves residential housing will very likely be regulated as a utility. Utilities, with their granted local monopoly, come under very stringent regulatory control. With their rates specified by law and mere failure to make a profit considered insufficient reason to abandon service, entering into the utility business could be likened to selling short in the stock market — the gains are bonded but the losses are not. A public utility is essentially backed against operating losses by the local tax base. A private utility, however, may tend to approach expansion of service into a relatively new field very cautiously.

INDUSTRIAL PARTICIPATION

The strongly regulated environment of utilities is not frequently attractive to industrialists. Traditionally, governmental regulation of industry has resulted in expenditure without payback. Becoming as heavily regulated as a utility is definitely not an attractive proposition. To achieve willing cooperation of industry, some assurance must be made that the industry will remain free to determine its operation independent of the existence of waste heat recovery systems. This can be accomplished by contract between the utility and the industry, but earlier assurances are needed. The concept of utility owned and operated heat recovery equipment, with the industry donating its otherwise wasted energy and benefiting through improved public image seems to be one which elicits a minimum of regulatory question during early negotiation.

SYSTEM FINANCING

Major differences exist between the approaches to financing of new projects between publically and privately owned utilities. A private utility may finance approximately 40 percent of the required capital by sale of stock with bonds supplying the remainder. Profit must be made to pay dividends to the shareholders. These dividends may be near 10 percent, requiring near 20 percent before taxes profit on that portion of the capital financed through stock sale. This is relatively expensive financing if viewed as an expense, similar to the view of the annuity for the 100 percent financing assumed for the public utility. The result is that a public utility may be able to undertake integrated energy supply situations which would not be profitable for a private utility.

CONSUMER INCENTIVE

Some incentive to subscribe to the system must be provided. Studies have shown that to achieve a significant penetration in the consumer market an *invisible* product requires a payback no more than 1-1/2 years. This would be a formidable barrier to an HPICES with subscriber owned and maintained equipment. Utility ownership of the in-house equipment will remove this barrier.

SPECIFIC CONSIDERATIONS FOR EVERETT SITE

There are no major institutional constraints to the implementation of the HP-ICES in Everett. There are a variety of possible ownership structures. The potential for growth in the central business district (CBD) and adjacent residential areas, the changing energy picture, and current upgrading of water and sewer lines create a receptive environment for the HP-ICES project.

Everett Franchise – The HP-ICES ownership, hereinafter the system, must obtain permission from the Everett administration to use city streets for the placement of mains and pipelines and to operate as a supplier of hot water heating. There are precedents in Everett for such franchises to include Washington Natural Gas Company, Snohomish County Public Utility District (PUD), the electric utility, and the municipal water and sewer utilities. The city administration supports the HP-ICES. The Everett Public Works Department, which monitors franchises, knows of no barriers to installation of the system.

The difficulty of avoiding other underground utility lines is not unique to the installation of the system in Everett. Coordination with sewer and water underground rehabilitation in Everett will reduce HP-ICES installation costs.

Everett Building Code – The Everett Building Department assumes jurisdiction of construction from the Public Works Department when the system goes from the public right-of-way over a property line. Everett, pursuant to the "State Building Act," Chapter 19.27 Revised Code of Washington (RCW), has adopted the Uniform Building Code, and more specifically the Uniform Mechanical Code, including Appendix A which applies to hot water systems. Review of the latter with the Building Department shows no apparent constraint to the system.

Permits – The issuance of the franchise or a building permit will trigger the application of the State Environmental Policy Act (SEPA) (RCW 43.21C). As in many states, SEPA parallels the requirements of the National Environmental Policy Act (NEPA), and Everett has, in turn, adopted ordinances which parallel the requirements of SEPA. The Shorelines Management Act (SMA) (RCW 90.58), may require a permit.

A full environmental impact statement (EIS) will probably be required because of the impact during installation and the potential impact on the city's direction of growth. Use of the optional "one step" permit procedure established by the Environmental Coordination Procedures Act (RCW 90.62) will expedite the permit process.

Displacement of Customers of Other Utilities and Fuel Suppliers – The HP-ICES will compete with the Snohomish County Public Utility District (PUD), the electric utility, and Washington Natural Gas for supplying space heating. The PUD has the cheapest electrical rates in the country, but it faces substantial price increases as demand exceeds the supply of cheap hydroelectric power from the Bonneville Power Administration (BPA) and expensive thermal power is brought on line. To eliminate resistance from the PUD, the developer should emphasize the growing market for more efficient end uses of the PUD's product. Removing the demand of some space heating will keep the prices down for end uses of electricity.

The PUD is a likely candidate to own and/or operate the HP-ICES. It could meld the rates for electrical power and hot water space heating. The above efforts can be pursued to mitigate the impact of displacing PUD customers.

The system will also partially compete with the gas utility. Washington Natural Gas currently obtains ample supplies from Canada and has reserves in Washington and Oregon. The Canadian price for gas will increase with deregulation of interstate sales in the U. S. This will make the HP-ICES more cost competitive.

A developer of the HP-ICES can argue that any displacement of utility customers in the CBD and surrounding neighborhoods will be compensated with new customers in other growth areas. There is also a mandate from the Federal and State Governments to conserve nonrenewable resources. The gas utility is part of a holding company called the Washington Energy Company which has diversified into solar energy products and other alternative energy sources. The utility has anticipated displacement of its customers over the long term. Furthermore, the gas utility is a possible owner and operator of the system.

The system will displace oil-fired forced air systems. Fuel oil distributors will need to diversify their activities. There have been few, if any, new fuel oil burners installed for space heating in Everett in the last year. There has been an increasing number of conversions from oil to natural gas in Everett. The current oil squeeze has emphasized the necessity for using oil for more appropriate end uses than space heating. The existing economic and political environment in Everett and the country, and the strong arguments for conservation, will serve to mitigate any resistance of the nonregulated fuel suppliers.

Community Acceptance – The Everett community is used to having a say in the management of their utilities, with the exceptions of telephone and natural gas. The city runs the water and sewer utility, and commissioners are elected to run the PUD electric utility. The current city administration, however, will defer involvement in any activity which can be conducted by the private sector. Furthermore, the existing municipal water and sewer utilities have not been without problems for the administration. In any case, political and community leaders will have a major input in choosing the ownership structure for the HP-ICES.

Private Ownership Financing – Regulation of the system is discussed in more detail below. The Washington State Utilities and Transportation Commission, hereinafter Commission, would probably assert jurisdiction over a privately owned HP-ICES system furnishing district heating. The Commission, therefore, has full control over the utility's authority to issue stock, or other evidence of interest or ownership, and bonds, notes, and other evidence of indebtedness, and to create liens on its property (RCW 80.08.020). A private utility in Everett would have access to the traditional forms of financing through equity and debt. Washington Natural Gas, as an example, is capitalized by 58% debt and 42% equity.

Private Ownership Taxation – Property Taxes, sales taxes and business and occupation taxes all add to the cost the customer will pay for heat from a private utility. These exist in Everett. To mitigate these constraints, legislation deferring the property tax in the early years of a system or reducing the tax on district heating utilities are possibilities with obvious political challenges. Lower rates for the sales and B&O* taxes on district heating would mitigate these constraints on the system.

Private Ownership Regulation – The regulatory authority of the Commission does not specifically include district heating systems (RCW 80.01.040). Municipal and publicly owned utilities are specifically excluded from most areas of regulation. Although the Commission has not asserted jurisdiction over Seattle Steam Company, a private steam district heating system for commercial buildings in Seattle, a strong argument can be made that the legislature intended to include an entity such as a private district heating utility. The added expense resulting from regulation must be weighed against increased consumer confidence. Pressures from other regulated utilities and the lack of other competitive nonregulated fuel sources other than oil will encourage regulation.

Major areas of regulation of income and service would include recovery of start-up loss, allowance for funds during construction, area of service, and quality of service. Because these areas have not been addressed before by the Commission for a hot water district heating system, new regulations will be necessary. The impact on the user and viability of the system will be significant.

The current Commission is sensitive to the energy situation in the state. It is holding generic rate hearings in August 1979 for the first time in decades. If the conservation potential of HP-ICES for Everett is apparent, the Commission should facilitate the rule-making process. The Commission could also be persuaded that regulation was not necessary because of existing competition from the other regulated and nonregulated fuel suppliers and the conservation potential of the HP-ICES.

Public Ownership Management Structures – Everett has authority to create and manage the HP-ICES. The City's attitude is discussed above. The City would be answerable to the customers, and the financing options are greater.

The existing PUD could operate the HP-ICES (RCW 54). The PUD's are municipal corporations of the state. They were organized to provide electric and/or water utility service to their owners, the people who formed the districts, on a nonprofit, cost of service basis. The PUD in Everett supplies electricity for the entire county and owns and manages several water districts. It is respected in the community.

A combination of public ownership with private management is another alternative.

Public Ownership Financing – A municipal utility in Everett would have access to traditional municipal financing (RCW 35.92). The type or combination of financing would depend on the city's goals. Assuming city ownership, would the city want to operate the system? Federal guarantees for the financing would have an obvious impact on the investment community.

*Business and Occupation Tax in the state of Washington is assessed at 0.44% of gross sales.

In Washington, the State Constitution prohibits public governing bodies from lending their credit to the private sector. The City, therefore, cannot grant loans to customers to assist with retrofitting their buildings for the HP-ICES. There is an effort in the state to amend the constitution which could help implementation of the HP-ICES and other energy conservation measures in the state.

The PUD has general and revenue bonding authority (RCW 54.24). It can also enter joint activities with the city.

Public Ownership Taxation – The municipal system may be required to make payments in lieu of taxes. The PUD which sells electric energy must pay a privilege tax for doing business in the state (RCW 54.28.020). Any city or town may levy a tax on the PUD's gross revenues from the sale of electricity (RCW 54.28.070). The cities and the State Department of Revenue would most probably also request authority to tax revenues from the sale of thermal energy in the form of district heating. Work with the appropriate state legislative committees will assist to clarify the taxing implications for each ownership and management structure.

SEATTLE, WASHINGTON

Site Description

Energy Source – In the South Seattle area, a cluster of light to medium industry has been identified with a low-grade waste heat dissipation of 5.9×10^{11} Btu/year (Table 8-7 details these sources), sufficient (with some means for annual storage) to provide the space heating and hot water heating requirements of 13,200 homes. The Duwamish River (navigable) separates the site into two autonomous sites. While tunneling beneath the river and elevated suspended pipelines above the river are means to couple the two sites, the expense associated with such means is unlikely to be worth the redundancy provided.

The western group is composed of two relatively larger magnitude sources in the form of cooling towers and two smaller, though somewhat warmer, sources in transformer substations. The Duwamish substation is 3-1/2 miles from the next nearest source. RRC estimates for the annual heating and hot water demand for a residence is 0.67×10^8 Btu/year. Hence, that station even at 100% recovery, 0% loss, COP = 3, yields only enough energy for approximately 270 residences equivalent and would logically be included in a later stage of system development.

The eastern grouping of identified energy sources extends from Northwest Glass in the south through the Massachusetts substation to the north, with future expansion possibilities southward to include Jorgensen Steel, and northward to include the Union substation.

The central cluster of six sources shown in Table 8-7 is composed of five relatively small sources and the large source of energy from Lone Star Cement's kilns. Compared to all other sources listed herein, this is probably the most difficult source with which to work. These kilns are cooled by radiation and natural convection; and to capture this energy without disturbing the heat balance on the kilns appears to be a formidable task. It is believed that this source should be considered an opportunity for future expansion of a system composed at the start of the other five smaller sources.

Table 8-7

SOUTH SEATTLE ENERGY SOURCES

	Location	Type Source	Magnitude		Temperature	
			Btu/Year	*R.E.	Summer (°F)	Winter (°F)
West of Duwamish	Duwamish Substation	Transformers (3) OA/FOA/FOA	12.2 x 10 ⁹	270	122	105
	Delridge Substation	Transformers (3) (FOA)	6.2 x 10 ⁹	140	115	100
	Bethlehem Steel Inc.	Cooling tower & pond	137 x 10 ⁹	3,082	100	85
	Ideal Basic Industries	Cooling tower	152 x 10 ⁹	3,420	90	75
	Totals		307.4 x 10 ⁹	6,912		
East of Duwamish	Lone Star Cement	Air cooling from kilns	169 x 10 ⁹	3,802	400	
	Mass. Substation	Transformers (2) (FOA)	8.54 x 10 ⁹	192	122	105
	South Substation	Transformers (6) (FOA)	30.2 x 10 ⁹	679	135	120
	PACCAR	Cooling water to sewer	18 x 10 ⁹	405	105	
	Northwest Glass	Cooling tower	32.9 x 10 ⁹	740	90	
		Sewer	8.8 x 10 ⁹	198	105	
	Rainier Brewery	Cooling tower	14.8 x 10 ⁹	333	90	75
	Totals		282.2 x 10 ⁹	6,349		
	Grand Totals		589.6 x 10 ⁹	13,261		

*R.E.: Residence equivalent; assumes COP — 3.0, 100% recovery, 0% loss.

The five smaller sources are composed of two transformer substations and three industrial concerns, distributed over a band 2.7 miles long and 1.1 miles wide bounded by Interstate 5 to the east, the Duwamish River to the west. Activity in this region is primarily industrial with some large commercial. To the north, the Seattle commercial district borders this area, while additional demand for the energy exists in medium to low density residential areas to the east of Interstate 5. Soil underlying the area is typical of river flood plains – sandy, gravelly loam, and should present no unusual problems for buried pipelines.

The surrounding communities for the east and west groups are well defined by the 1970 Census. The Census Tract Map is presented in Figure 8-13. The pertinent characteristics of census tracts adjacent to the identified low-grade waste heat streams are collected in Tables 8-8 through 8-10.

The housing density in housing units per square mile, and the fraction of such units which are contained in multiple housing unit structures (five or more units per structure) is presented in Tables 8-8 and 8-9 for the east and west groupings, respectively. The east group is clearly a higher density residential area than the west group. As housing density is known to correlate strongly with cost competitiveness in preliminary design of district heating systems, the eastern grouping was selected for more intense study.

One of the several advantages to a community energy system using several energy sources lies in the ease with which such a system can be implemented in stages. A likely four-phase project concerning the east group would start by including the south substation and the Rainier Brewery, serving an appropriately sized user complex. During the second phase, Paccar and Northwest Glass could be incorporated as the distribution system expanded southward and northward toward the City Center. During a third expansion phase, the techniques developed during work with the south substation could be applied directly to the Massachusetts substation as the system expanded toward the Central business core. During a final phase, a tradeoff between the difficulty of recovering the Lone Star source versus the difficulty of crossing the waterway with the ideal cement energy would be made. Whichever was chosen would allow the system expansion into the City Center.

A particularly attractive complex of potential users for the system's first stage is the low income housing developments known as Rainier Vista and Holly Park. The Rainier Vista complex is situated 1.6 miles eastward of the point midway between the two sources at the corner of Census Tracts 100, 101, 103, and 104, extending partially into each tract. Holly Park straddles the demarcation between Census Tract 110 and 111, approximately 1.6 miles further south. Dwelling in both developments are single-story duplex and four-plex layouts of standard frame construction, built over crawl spaces. Heating systems for these units are either electric baseboard or gas-fired wall furnaces.

System Description and Growth Plan, Seattle Site

The first step system for the Seattle area was analyzed in some detail in a search for the most beneficial combination of heat pump size, system supply temperature, system return temperature, storage volume, and service options and system size option. Both central and distributed strategies

CENSUS TRACTS CITY OF SEATTLE

**Table 8-8
EAST GROUP**

Census Tract No.	Area Sq. Mi.	Total Housing Units	Density HU/Mi²	Percent Multiple Dwelling
79	0.256	1,958	7,520	64
81	0.317	1,282	4,310	99
82	0.136	1,992	14,960	83
83	0.102	2,725	25,610	98
84	0.141	1,977	12,570	95
85	0.184	2,015	9,610	92
86	0.270	1,528	5,090	68
87	0.281	1,570	4,700	35
88	0.352	1,510	3,850	15
89	0.455	2,098	3,980	24
90	0.295	972	2,970	40
91	0.166	822	5,020	85
92	0.109	575	7,040	97
93	3.673	649	180	46
94	0.688	1,981	3,040	26
95	0.944	2,290	2,340	18
100	1.230	2,941	2,380	21
101	1.020	2,176	2,080	10

**Table 8-9
WEST GROUP**

Census Tract No.	Area Sq. Mi.	Total Housing Units	Density HU/per Sq. Mi.	Percent Multiple Dwelling
96	0.725	2,095	2,890	20
97	1.227	4,395	3,580	12
98	0.720	2,571	3,570	14
99	2.673	1,701	640	15
105	0.627	2,315	3,690	26
106	0.973	2,052	3,140	15
107	0.841	1,955	2,320	7
108	1.680	951	570	3

Table 8-10
HEATING SYSTEM DATA

Census Tract No.	Total Housing Units	Steam or Hot Water	Central Forced Air	Electric Baseboard	Other (Includes Unheated Structures)	Air Conditioning (Percent)
East Group						
79	1,958	808	469	354	325	<div><5%</div> <div></div> <div><5%</div>
81	1,282	1,188	37	—	57	
82	1,992	1,836	78	33	45	
83	2,725	2,323	57	238	107	
84	1,977	1,532	98	214	133	
85	2,015	1,414	100	400	101	
86	1,528	899	224	79	326	
87	1,570	366	457	268	479	
88	1,510	262	708	1,119	421	
89	2,098	236	715	495	652	
90	972	267	271	175	259	
91	822	666	47	21	88	
92	575	570	—	—	5	
93	649	109	278	206	56	
94	1,981	138	634	617	5	
95	2,290	480	784	521	505	
100	2,941	359	1,394	503	685	
101	2,176	101	1,111	359	605	
West Group						
96	2,095	271	1,143	361	220	<div><5%</div> <div></div> <div><5%</div>
97	4,395	320	2,604	810	661	
98	2,571	169	1,750	378	274	
99	1,701	93	788	348	472	
105	2,315	143	1,163	618	391	
106	3,052	72	1,865	723	392	
107	1,955	31	908	308	708	
108	951	27	331	282	311	

were optimized separately, and the final comparison was made based upon a system which brings out the best advantages of each strategy. The system is shown schematically in Figure 8-14.

The final system selected incorporates central heat pump strategy. The central heat pump has a capacity of 7.6 million Btu/hr (425 tons) and provides space heating needs and domestic hot water production of 448 housing units. A nominal supply temperature of 160°F and return temperature of 75°F was indicated. Nominally, 4 individual units of just over 100 tons each are indicated. These units are controlled via the demand/storage conditions in an on-off mode, avoiding partial load inefficiencies associated with heat pumps. The system does not incorporate any cooling tower or auxiliary heat dissipation means, as the existing heat dissipation means which serve as an energy source will remain operable. In the case of the transformers, withdrawing their waste energy at a temperature level below the switch temperature for the forced air convectors will simply mean that the convectors will not come on as long as the heating system demands energy. In the case of the brewery cooling tower, precooling the hot water enroute to the cooling tower will allow a thermostatic bypass of the tower and fan system under demand conditions. Finally, for the warm water outfall, existing dissipation mechanism is adequate whether or not the HP-ICES demands energy.

A hot storage tank of approximately 45,000 gallons is indicated for the system. A second identical tank is therefore required to maintain the required volume of water under all charge-discharge conditions. The combined sources are adequate to supply the required demands except on Sundays. The storage tank operates as a reserve of energy for Sunday demands as well as allowing the heat pumps to operate in an on-off mode rather than to accept partial load inefficiencies.

A transmission pipeline approximately 1.65 miles in length is required from the sources of waste energy to the user complex. The relatively low system peak temperatures indicated for the system allow use of insulated plastic pipe, directly buried. Cost of this material versus diameter is presented on Figure 1-6 as Item S-6. Extrapolation to the relatively small line indicated (5-inch diameter) was assumed to be no higher than Line S-5.

The distribution network is shown, tentatively, in Figure 8-15.

Estimated Performance, Seattle Site

The system provides space heating and domestic hot water demands for 448 housing units. Figure 8-16 presents an energy flow diagram showing representative performance of the system as indicated by annual total energies. The total annual energy furnished to the subscribers is 3×10^{10} Btu, distributed approximately 30 percent to domestic hot water production and 70 percent to space heating demand. Fossil fuel is used in topping on scattered occasions throughout the winter heating season, mostly on Sundays when the available energy from the sources is reduced. Fuel burned in the central topping boiler sums to 0.047×10^{10} Btu/year, approximately 1-1/2 percent of the total energy furnished.

Thermal losses in the transmission and distribution systems cumulate to 0.13×10^{10} Btu/year, approximately 4 percent when compared to the energy furnished.

HPICES SCHEMATIC, SEATTLE SITE

TENTATIVE MAIN PIPE LAYOUT – SEATTLE SITE

SUB-MAINS AND FEEDERS OMITTED FOR CLARITY

SEATTLE SITE HPICES
REPRESENTATIVE OPERATION (ANNUAL TOTAL)

UNITS: 10^{10} Btu/yr

Pump power required to overcome flow work in the transmission and distribution systems aggregates to 0.012×10^{10} Btu/year. The flow work itself (75 percent of the pump energy or 0.0087×10^{10} Btu/year) appears as thermal energy in the circulating water, tending to compensate for the system thermal losses.

Electric input to the heat pump compressor is a significant fraction of the total energy at 0.92×10^{10} Btu/year, but allows the elevation of 2.15×10^{10} Btu/year from the waste energy sources which would otherwise be wasted.

Summing the electric inputs to heat pump compressor and transmission pumps yields 0.935×10^{10} Btu/year (electrical). At an overall generation, transmission, and distribution efficiency of 30 percent, the electric inputs will require 3.116×10^{10} Btu of fossil fuel burned at some electric generation plant. Generation, transmission, and distribution losses for the electric system are aggregated to 2.18×10^{10} Btu/year.

Performance of a conventional alternate system to provide the same service is displayed in Figure 8-17. To deliver the space heating demand of 2.1×10^{10} Btu/year, the conventional oil furnace (60 percent efficiency assumed) consumes 3.51×10^{10} Btu/year. Stack losses and burner inefficiencies aggregate to 1.41×10^{10} Btu/year. The electrically fired hot water heater provides the 0.9×10^{10} Btu/year hot water demand at 100 percent efficiency. To generate this electric input in the remote generating station requires burning 3.0×10^{10} Btu/year of fossil fuel and results in a combined loss from generation, transmission and distribution of 2.10×10^{10} Btu/year.

The total input of oil for the HP-ICES is 3.116×10^{10} Btu/year. At 140,000 Btu/gallon and 42 gallons/barrel, an expenditure of 5,299 barrels per year is indicated. The conventional alternate system requires 6.5×10^{10} Btu from oil input, or 11,071 barrels per year. A net savings of 5,772 barrels of oil per year can be achieved by implementing this system.

Figure 8-18 presents system operation under peak load conditions. The basis for this figure is the predicted system operation, average over 24 hours, for the day with highest total heating demand in the "typical reference year". During the several preceding days, demand had exceeded capacity, so that the storage tank was depleted by this time and the system was requiring topping energy at the rate of 1.53×10^6 Btu/hr. Boiler inefficiencies and stack losses absorb 0.23×10^6 Btu/hr with the remainder delivered to the distribution system. At full capacity, the central heat pumps withdraw 5.31×10^6 Btu/hr from the energy source and require 2.30×10^6 Btu/hr of electric power. An additional 0.103×10^6 Btu/hr of electric input to the transmission/distribution pumps delivers 0.078×10^6 Btu/hr to overcome flow work through 75 percent efficient pumps. The combined electrical demand (2.42×10^6 Btu/hr) requires the expenditure of 8.01×10^6 Btu/hr of fossil fuel at the generating plant. Total fossil fuel consumption is found as the sum of the generating plant expenditure and the topping boiler fuel flow at 9.54×10^{10} Btu/hr. The total energy demand under these conditions is 8.31×10^6 Btu/hr of which 88 percent is required for space heating and the remaining 12 percent satisfies the hot water demand.

**SEATTLE SITE, CONVENTIONAL SYSTEM
REPRESENTATIVE OPERATION (ANNUAL TOTAL)**

UNITS: 10^{10} Btu/yr

SEATTLE SITE
HPICES
PEAK DEMAND OPERATION

UNITS: 10^6 Btu/hr

The energy flow diagram for a conventional system providing the same service is presented in Figure 8-19 and requires a total oil flow of 15.56×10^6 Btu/hr of which 22 percent is required in the central electrical generating plant and 78 percent in the home oil burning furnaces. The net savings achieved by the HP-ICES in peak mode operation is thus predicted as the difference in total fuel requirements, 6.02×10^6 Btu/hr.

Under peak demand conditions, the HP-ICES second law efficiency calculates to 4.52%, again roughly double that of the conventional system: 2.87%.

Economic Analysis

The total capital cost of the HP-ICES at the Seattle site is calculated from the size of major system elements at \$1.86 million (1978). The breakdown of the capital cost is presented in Table 8-11. A large fraction of the total system cost is devoted to installed pipelines, 49 percent for the distribution system, and 17 percent for the transmission system. The cost predictions for these elements are based upon actual experience in Sweden. The contingency factor represents approximately 40 percent of the remaining hardware items.

The life cycle cost analysis for this system is presented in Table 8-12. By the assumed system start date (1985), inflation has increased the total cost to \$2.62 million.

For sample payback analysis, the system net in the first year *before capital costs* is ratioed to the system total cost. The net displayed in the eighth column of Table 8-12 is the net after capital costs. Adding the first year capital cost displayed at the top of the third column to the first year net and ratioing to the system first cost yields a simple return on investment of 14 percent and a payback of slightly over seven years.

Table 8-11
HP-ICES COST BREAKDOWN AT SEATTLE SITE

	Calculated Cost 1978 \$	Percentage of Total Calculated Cost
Central heat pumps	130,908	7
Insulated storage tanks (2)	64,536	3
Distribution system (installed)	915,760	49
Topping/backup boiler	82,719	4
User heat exchangers	109,976	6
Transmission pipeline (installed)	312,000	17
Hardware Total	1,615,899	
Contingency	247,106	14
Total First Cost	1,863,005	100

SEATTLE SITE
CONVENTIONAL SYSTEM
PEAK LOAD PERFORMANCE

UNITS 10^6 Btu/hr

Table 8-12

CENTRAL SYSTEM
ECONOMIC ANALYSIS
VERSION 2.0

ASSUMPTIONS

CURRENT ENERGY COSTS (BASE DOLLARS)

USER ENERGY COST (\$/1000 BTU) 3.571 (CONSUMED AT .60 EFFICIENCY)
FOSSIL TOPPING COST (\$/GAL) .4000 (NO6 FUEL OIL CONSUMED AT 0.85 EFFICIENCY)
PUMP AND FAN ENERGY COST (\$/KW-HR) .0400

PLANT LIFE (YEARS) 30.00 (START OF PLANT OPERATION - 1985)

AFTER TAX COST OF CAPITAL .0800

ESCALATION RATES

GENERAL INFLATION RATE/YEAR .0500
LAVOR ESCALATION RATE/YEAR .0600
FOSSIL ENERGY ESCALATION RATE/YEAR .1340
ELECTRICAL ESCALATION RATE/YEAR .1140

NET PRESENT VALUE AT 0.08 = .1622E+08

INTERNAL RATE OF RETURN = .2470

SPACE HEATING DEMANDS SUPPLIED (BTU/YEAR) .21053E+11

HOT WATER DEMANDS SUPPLIED (BTU/YEAR) .89910E+10

SPACE COOLING DEMANDS SUPPLIED (BTU/YEAR) 0.

TOTAL SYSTEM COST (1985) AT START OF SYSTEM OPERATION .2621E+07

CONVENTIONAL ALTERNATE SYSTEM COST .0780E+07

YEAR	SALES	CAP. COSTS	OPERATION	FUEL	ELECTRIC	LOAN INT	NET	LOANS	PV AT .08
1985	.6936E+06	.2380E+06	.8353E+05	1782.	.2369E+06	0.	.1334E+06	0.	.1236E+06
1986	.7619E+06	.2380E+06	.8813E+05	2020.	.2639E+06	0.	.1699E+06	0.	.1457E+06
1987	.8387E+06	.2380E+06	.9297E+05	2291.	.2939E+06	0.	.2115E+06	0.	.1679E+06
1988	.9250E+06	.2380E+06	.9809E+05	2598.	.3274E+06	0.	.2589E+06	0.	.1903E+06
1989	.1022E+07	.2380E+06	.1035E+06	2946.	.3648E+06	0.	.3178E+06	0.	.2129E+06
1990	.1131E+07	.2380E+06	.1092E+06	3341.	.4064E+06	0.	.3743E+06	0.	.2359E+06
1991	.1254E+07	.2380E+06	.1152E+06	3789.	.4527E+06	0.	.4444E+06	0.	.2593E+06
1992	.1392E+07	.2380E+06	.1215E+06	4296.	.5043E+06	0.	.5241E+06	0.	.2831E+06
1993	.1548E+07	.2380E+06	.1282E+06	4872.	.5618E+06	0.	.6148E+06	0.	.3075E+06
1994	.1723E+07	.2380E+06	.1352E+06	5525.	.6258E+06	0.	.7180E+06	0.	.3326E+06
1995	.2001E+07	.2380E+06	.1427E+06	6265.	.6972E+06	0.	.9171E+06	0.	.3933E+06
1996	.2223E+07	.2380E+06	.1505E+06	7105.	.7766E+06	0.	.1051E+07	0.	.4172E+06
1997	.2472E+07	.2380E+06	.1588E+06	8057.	.8652E+06	0.	.1202E+07	0.	.4421E+06
1998	.2754E+07	.2380E+06	.1675E+06	9136.	.9638E+06	0.	.1375E+07	0.	.4681E+06
1999	.3070E+07	.2380E+06	.1768E+06	.1036E+05	.1074E+07	0.	.1571E+07	0.	.4953E+06
2000	.3426E+07	.2612E+06	.2113E+06	.1175E+05	.1196E+07	0.	.1746E+07	0.	.5097E+06
2001	.3824E+07	.2612E+06	.2229E+06	.1332E+05	.1332E+07	0.	.1998E+07	0.	.5400E+06
2002	.4280E+07	.2612E+06	.2352E+06	.1511E+05	.1484E+07	0.	.2285E+07	0.	.5717E+06
2003	.4790E+07	.2612E+06	.2481E+06	.1713E+05	.1654E+07	0.	.2610E+07	0.	.6048E+06
2004	.5364E+07	.2612E+06	.2618E+06	.1943E+05	.1842E+07	0.	.2980E+07	0.	.6393E+06
2005	.6145E+07	.2612E+06	.2762E+06	.2203E+05	.2052E+07	0.	.3533E+07	0.	.7019E+06
2006	.6874E+07	.2612E+06	.2914E+06	.2499E+05	.2286E+07	0.	.4011E+07	0.	.7377E+06
2007	.7657E+07	.2612E+06	.3074E+06	.2833E+05	.2547E+07	0.	.4553E+07	0.	.7755E+06
2008	.8424E+07	.2612E+06	.3247E+06	.3213E+05	.2837E+07	0.	.5169E+07	0.	.8152E+06
2009	.9269E+07	.2612E+06	.3421E+06	.3644E+05	.3160E+07	0.	.5869E+07	0.	.8569E+06
2010	.1024E+08	.2612E+06	.3604E+06	.4132E+05	.3521E+07	0.	.6663E+07	0.	.9009E+06
2011	.1218E+08	.2612E+06	.3808E+06	.4685E+05	.3922E+07	0.	.7565E+07	0.	.9471E+06
2012	.1357E+08	.2612E+06	.4017E+06	.5313E+05	.4364E+07	0.	.8590E+07	0.	.9956E+06
2013	.1544E+08	.2612E+06	.4238E+06	.6025E+05	.4867E+07	0.	.9752E+07	0.	.1047E+07
2014	.1727E+08	.2612E+06	.4471E+06	.6823E+05	.5422E+07	0.	.1107E+08	0.	.1100E+07

Accounting for the time value of money, the system internal rate of return is 24.7 percent and the net present value at the start date is \$16.2 million (1985).

The results of a sensitivity analysis performed for this system against the escalation rate for fuel are presented in Figures 8-20 and 8-21. In these figures, the effect of inflation is removed by presenting fuel escalation rate in real (constant) dollars, and the escalation rate of electrical power is constrained to equal that of fuel oil. Labor escalation of 1 percent above the underlying general inflation rate is assumed for all analyses save the zero escalation case, where labor also is assumed to follow general inflation.

The net present value at the 1985 start date and the first year net, before and after capital costs, are presented in Figure 8-20. This system is predicted to be profitable from the start, irrespective of fuel escalation.

The effect of various assumed fuel escalation rates upon the system internal rate of return is presented in Figure 8-21. Even without increase in the real cost of fuel, the system shows an internal rate of return well above the cost of capital.

SAN ANTONIO, TEXAS

Community Description

The city of San Antonio, Texas, was chosen as a second alternate site for analysis. This site is geometrically similar, thus differences between the San Antonio and Seattle sites will be largely a result of the differing weather patterns. Figure 8-22 shows the northwestern portion of the city.

A source of heat which is believed comparable to that identified for the first step of the Seattle site exists in the combination of the dissipation from three transformer substations and a large medical center. The substations define the corners of a triangle approximately 2-1/2 miles on a side, with the medical center in the northern corner.

Information on the surrounding community is compiled in Tables 8-13 and 8-14 from the 1970 Census. In general, housing densities in this region of San Antonio are somewhat lower than the selected Seattle site. With the exception of Census Tract 1808, there is not a large fraction of multiple housing structures, steam or hot water heating systems are less prevalent, central forced air systems are more prevalent, and air conditioning systems are nearly universal.

Census Tract 1808 was chosen as nearly comparative with the first step system at the Seattle site.

System Description

The indicated system for the San Antonio site is quite different from that of Seattle. Whereas in the latter, the inherent capability of the distributed strategy to provide space cooling with little or no additional equipment was not particularly beneficial, for the former this capability adds very materially to the system benefit. This is the major reason why a distributed strategy shows better cost competitiveness for the San Antonio site. The system is shown schematically in Figure 8-23.

SENSITIVITY OF NET PRESENT VALUE AND FIRST YEAR NET TO FUEL ESCALATION RATE

**SENSITIVITY OF NET PRESENT VALUE AND FIRST
YEAR NET TO FUEL ESCALATION RATE**

SAN ANTONIO, TEXAS (NORTHWESTERN PORTION OF CITY)

Figure 8-22

Table 8-13
HOUSING DENSITY NEAR SAN ANTONIO SITE

Census Tract No.	Area Sq. Mi.	Total Housing Units	Density HU/Sq. Mi.	Percent Multiple Dwelling
1802	1.608	3,316	2,062	27
1806	2.265	2,578	1,138	4
1807	2.388	1,713	717	42
1808	0.661	1,365	2,064	70
1809	2.183	4,646	2,127	7
1810	2.633	1,060	402	18
1811	1.392	1,321	949	19
1812	1.337	537	401	0
1813	2.228	711	311	0
1814	2.536	119	47	0
1815	3.301	202	61	64

Table 8-14
HEATING SYSTEM DATA

Census Tract No.	Total Housing Units	Steam or Hot Water	Central Forced Air	Electric "Built In" Units	Other (Includes Unheated Structures)	Air Conditioning (Percent)
1802	3,316	10	1,416	122	1,768	80
1806	2,578	31	2,168	34	327	97
1807	1,713	—	1,542	54	117	99
1808	1,365	—	1,073	80	212	97
1809	4,646	9	1,911	116	2,610	88
1810	1,060	—	720	31	309	98
1811	1,321	5	1,293	14	9	100
1812	537	—	474	17	46	100
1813	711	6	697	—	8	95
1814	119	—	61	—	58	69
1815	202	—	173	11	18	100

SAN ANTONIO SITE HP-ICES PREFERRED STRATEGY SCHEMATIC

Water source heat pumps, of 1.65-ton capacity, distributed in each housing unit, form the crux of the system. This capacity meets 96 percent of the summer peak cooling load. It is assumed that all user systems to be retrofit are central forced air systems.

The water source heat exchanger for these heat pumps is arranged to include a flow reversing pump which can overcome the pressure difference between the the systems supply and return lines. This arrangement allows energy extracted from users in the cooling mode to be furnished directly to users demanding energy in the heating mode. Savings in cooling tower operation time. This situation is expected to be important under conditions where widely variant building characteristics are incorporated. Shade patterns or variations in local terrain may also be recipients of this benefit. Savings due to this mode of operation in the model herein studied, where all users are considered identical, would be a lower percentage than with any other user mix.

Equipment associated with the capture of waste energy will be either water-to-water heat exchangers (in the case of the medical center cooling towers) or oil-to-water heat exchangers (in the case of the transformer substations).

It is assumed that transmission pipeline costs will be the same in the alternate site as in the primary site.

HP-ICES Performance for San Antonio

The HP-ICES provides space cooling as well as space heating and domestic hot water production for 448 housing units. Representative performance is presented in Figure 8-24 as the annual total energy flow for the system. A fuel input of 5.997×10^{10} Btu/year at the electric generation plant is required to generate the system total electric demand of 1.80×10^{10} Btu/year. In the heating mode, 0.70×10^{10} Btu/year are withdrawn from the waste energy source through the expenditure of 0.36×10^{10} Btu/year compressor electrical power and 0.012×10^{10} Btu/year pump power. A contribution of 0.42×10^{10} Btu/year to the heating demands is made directly from the waste energy from the cooling mode, due to the inherent system capability to furnish energy to hot water heating in the space cooling mode.

An annual demand of 2.64×10^{10} Btu energy extracted from the user space in the cooling mode is furnished through the expenditure of 1.37×10^{10} Btu/year compressor power and 0.05×10^5 Btu/year for water circulating pumps. The system puts 0.42×10^{10} Btu/year of this energy to useful service in the heating mode, rejecting the remainder through the central cooling tower.

A conventional system operating at the San Antonio site will show annual performance as depicted in Figure 8-25. The annual space heating demand of 0.59×10^{10} Btu/year is satisfied through the expenditure of 0.98×10^{10} Btu of fossil fuel in the home furnaces and results in a burner/stack loss of 0.37×10^{10} Btu.

Electric energy to heat domestic water (0.90×10^{10} Btu) and run the air conditioning compressor (1.32×10^{10}) requires the expenditure of 7.4×10^{10} Btu in the generating plant and results in generation, transmission and distribution losses of 5.18×10^{10} Btu/year.

**SAN ANTONIO SITE
HP-ICES REPRESENTATIVE PERFORMANCE**

UNITS: 10^{10} Btu/yr

**SAN ANTONIO SITE
CONVENTIONAL SYSTEM
REPRESENTATIVE PERFORMANCE**

UNITS: 10^{10} Btu/yr

Total oil consumption for the conventional system at the alternate site sums to 8.38×10^{10} Btu/year. The HP-ICES requires 6.00×10^{10} Btu/year to deliver identical service. Hence, the HP-ICES would effect a savings of 2.38×10^{10} Btu/year. This corresponds to 170,000 gallons of oil or 4,048 barrels of oil saved per year.

Peak Performance Analysis

Peak loads at the alternate site occur during the cooling mode. The average load over that day which aggregates the greatest cooling demand is chosen as realistic basis for prediction of peak load performance. In Figure 8-26, the energy flow diagram for the HP-ICES under these conditions is presented. A space cooling demand that 8.82×10^6 Btu/hr be withdrawn from the user space requires the generation of 4.58×10^6 Btu/hr electrical to operate the heat pump compressors, and 0.061×10^6 Btu/hr electrical to operate the water circulation pumps. The total system electric demand (4.64×10^6 Btu/hr) requires burning 15.47×10^6 Btu/hr at the electric generating plant. The system hot water demand of 1.03×10^6 Btu/hr is supplied directly from the energy removed from the user space, having a surplus of 12.43×10^6 Btu/hr to be rejected through the atmosphere through the system cooling tower.

Peak performance of a conventional system at the San Antonio site is depicted by the energy flow diagram of Figure 8-27. A total electric demand of 5.44×10^6 Btu/hr is required to operate the air conditioners and hot water heaters, distributed 4.41×10^6 Btu/hr and 1.03×10^6 Btu/hr, respectively. To provide this demand, the energy input to the electric generating plant is 17.82×10^6 Btu/hr and results in generation, transmission and distribution losses of 12.38×10^6 Btu/hr. The energy withdrawn from the user space by the air conditioners (8.82×10^6 Btu/hr) combined with the electric power required to drive their compressors, yields 13.23×10^6 Btu/hr rejected to the atmosphere by the air conditioners.

Comparing the peak load performance of the HP-ICES to the peak load performance of the conventional system, the HP-ICES requires 2.35×10^6 Btu/hr less fuel than the conventional system. Expressed as a percentage of the conventional (assumed presently operating) system, a savings of 13 percent is predicted.

Economic Analysis, San Antonio

The capital cost of the HP-ICES applied to the alternate site is predicted at \$3.87 million (1978). Table 8-15 presents a breakdown of this cost by major system element. The costs of buried transmission and distribution lines again form the major share of the original cost at 53 percent of the total. The cost estimation means for these pipes presupposes the requirement for insulation. The very low temperature difference between the circulating water and the earth results in a minimal need for insulation, per se. The insulation does provide protection from sharp objects during back-fill operations. Additionally, some protection from vermin is also provided. The cost of insulation is therefore retained in the cost aggregate despite the lack of need for its thermal property.

SAN ANTONIO SITE HP-ICES PEAK LOAD OPERATION

UNITS: 10^6 Btu/hr

**SAN ANTONIO SITE
CONVENTIONAL SYSTEM
PEAK LOAD PERFORMANCE**

UNITS: 10^6 Btu/hr

Table 8-15
COST OF MAJOR SYSTEM ELEMENTS
SAN ANTONIO

	<u>Cost</u> <u>1978 \$</u>	<u>Percentage</u> <u>of Total</u> <u>First Cost</u>
Distributed heat pumps	989,363	26
Storage tanks	60,148	2
Distribution system (installed)	1,623,248	42
Topping/backup boiler	73,138	2
Central cooling tower (installed)	134,000	3
Source heat exchanger	63,159	2
Transmission pipeline (installed)	416,000	11
	<u>3,359,056</u>	
Total hardware cost contingency	511,520	13
Total First Cost	3,870,576	100

A life cycle cost analysis for this system is presented in Table 8-16. When compared to the primary site, this system is less desirable. A first year net before capital costs of \$268,000 is summed from the 1985 data of columns 3 and 8. When ratioed to the capital cost, inflated to 1985, a simple return of approximately 5 percent and a simple payback period of 20 years is predicted. The required annuity payment on the 100 percent first cost financing assumption is greater than the first year net, i.e., the system does not make a profit after capital costs. A loan to cover the first year loss shows for the second year. Interest rate is assumed at 8 percent. The system continues to be unable to make its full capital annuity payment until 1994, where the sign change in the final right-hand column indicates that the system could meet its full annuity payment (however, it must apply all additional income to paying short-term loan interest). The sign change in the net columns between 1999 and 2000 indicates that the system now meets its full annual annuity payment and the total annual interest on short-term loans. This additional income can be applied to reducing the principal of short-term loans. Short-term loans are finally retired in 2007, with seven years remaining of the system life.

The net present value of the system is \$2.66 million with an internal rate of return just below the cost of capital at 7.6 percent.

A sensitivity analysis, performed against the escalation of fuel cost for this system, shows that under economic conditions where the real value of fuel increases at less than 5 percent per year, the system fails to repay its original investment over the 30-year life.

Table 8-16

DISTRIBUTED SYSTEM
ECONOMIC ANALYSIS
VERSION 2.0

ASSUMPTIONS

CURRENT ENERGY COSTS (BASE DOLLARS)
USED ENERGY COST (\$/1000 BTU) 3.571 (CONSUMED AT .60 EFFICIENCY)
FOSSIL TOPPING COST (\$/GAL) .4000 (NO6 FUEL OIL CONSUMED AT 0.85 EFFICIENCY)
PUMP AND FAN ENERGY COST (\$/KW-HR) .0400

PLANT LIFE (YEARS) 30.00 (START OF PLANT OPERATION = 1985)

AFTER TAX COST OF CAPITAL .0800

ESCALATION RATES

GENERAL INFLATION RATE/YEAR .0500
LABOR ESCALATION RATE/YEAR .0600
FOSSIL ENERGY ESCALATION RATE/YEAR .1340
ELECTRICAL ESCALATION RATE/YEAR .1140

NET PRESENT VALUE AT 0.08 = .2661E+07
INTERNAL RATE OF RETURN = .7574E-01

SPACE HEATING DEMANDS SUPPLIED (BTU/YEAR) .58726E+10
HOT WATER DEMANDS SUPPLIED (BTU/YEAR) .89910E+10
SPACE COOLING DEMANDS SUPPLIED (BTU/YEAR) .26453E+11

TOTAL SYSTEM COST (\$1985) AT START OF SYSTEM OPERATION .5446E+07

CONVENTIONAL ALTERNATE SYSTEM COST .1402E+07

YEAR	SALES	CAP. COSTS	OPERATION	FUEL	ELECTRIC	LOAN INT	NET	LOANS	PV AT .08
1985	.9487E+06	.5676E+06	.2075E+06	0.	.4728E+06	0.	-.2993E+06	0.	-.2771E+06
1986	.1029E+07	.5676E+06	.2190E+06	0.	.5267E+06	.2394E+05	-.3080E+06	.2993E+06	-.2435E+06
1987	.1119E+07	.5676E+06	.2310E+06	0.	.5868E+06	.4858E+05	-.3151E+06	.6073E+06	-.2115E+06
1988	.1219E+07	.5676E+06	.2437E+06	0.	.6537E+06	.7378E+05	-.3201E+06	.9223E+06	-.1810E+06
1989	.1330E+07	.5676E+06	.2571E+06	0.	.7282E+06	.9939E+05	-.3226E+06	.1242E+07	-.1519E+06
1990	.1453E+07	.5676E+06	.2712E+06	0.	.8112E+06	.1252E+06	-.3218E+06	.1565E+07	-.1239E+06
1991	.1591E+07	.5676E+06	.2968E+06	0.	.9037E+06	.1509E+06	-.3279E+06	.1887E+07	-.1033E+06
1992	.1745E+07	.5676E+06	.3251E+06	0.	.1007E+07	.1772E+06	-.3321E+06	.2215E+07	-.8369E+05
1993	.1915E+07	.5676E+06	.3566E+06	0.	.1121E+07	.2037E+06	-.3339E+06	.2547E+07	-.6513E+05
1994	.2106E+07	.5676E+06	.3915E+06	0.	.1249E+07	.2305E+06	-.3330E+06	.2881E+07	-.4748E+05
1995	.2450E+07	.6981E+06	.3546E+06	0.	.1392E+07	.2571E+06	-.2518E+06	.3214E+07	.2260.
1996	.2686E+07	.6981E+06	.3740E+06	0.	.1550E+07	.2772E+06	-.2135E+06	.3466E+07	.2531E+05
1997	.2950E+07	.6981E+06	.3946E+06	0.	.1727E+07	.2943E+06	-.1641E+06	.3679E+07	.4788E+05
1998	.3244E+07	.6981E+06	.4163E+06	0.	.1924E+07	.3075E+06	-.1017E+06	.3843E+07	.7005E+05
1999	.3572E+07	.6981E+06	.4392E+06	0.	.2143E+07	.3156E+06	-.2403E+05	.3945E+07	.9191E+05
2000	.3938E+07	.6981E+06	.4633E+06	0.	.2388E+07	.3175E+06	.7145E+05	.3969E+07	.1135E+06
2001	.4346E+07	.6981E+06	.5070E+06	0.	.2660E+07	.3118E+06	.1695E+06	.3897E+07	.1301E+06
2002	.4802E+07	.6981E+06	.5546E+06	0.	.2963E+07	.2982E+06	.2868E+06	.3728E+07	.1464E+06
2003	.5310E+07	.6981E+06	.6091E+06	0.	.3301E+07	.2753E+06	.4264E+06	.3441E+07	.1626E+06
2004	.5877E+07	.6981E+06	.6688E+06	0.	.3677E+07	.2412E+06	.5918E+06	.3015E+07	.1787E+06
2005	.6724E+07	.9106E+06	.6055E+06	0.	.4096E+07	.1938E+06	.9177E+06	.2423E+07	.2208E+06
2006	.7431E+07	.9106E+06	.6384E+06	0.	.4563E+07	.1204E+06	.1198E+07	.1505E+07	.2424E+06
2007	.8270E+07	.9106E+06	.6740E+06	0.	.5084E+07	.2462E+05	.1527E+07	.3078E+06	.2643E+06
2008	.9161E+07	.9106E+06	.7111E+06	0.	.5663E+07	0.	.1816E+07	0.	.2864E+06
2009	.1002E+08	.9106E+06	.7502E+06	0.	.6309E+07	0.	.2115E+07	0.	.3088E+06
2010	.1112E+08	.9106E+06	.7914E+06	0.	.7028E+07	0.	.2453E+07	0.	.3317E+06
2011	.1241E+08	.9106E+06	.8450E+06	0.	.7829E+07	0.	.2805E+07	0.	.3512E+06
2012	.1378E+08	.9106E+06	.9087E+06	0.	.8722E+07	0.	.3201E+07	0.	.3710E+06
2013	.1531E+08	.9106E+06	.1043E+07	0.	.9714E+07	0.	.3647E+07	0.	.3914E+06
2014	.1702E+08	.9106E+06	.1142E+07	0.	.1082E+08	0.	.4149E+07	0.	.4123E+06

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9.0 COMPONENT TESTING REQUIREMENTS

Attention has been paid to develop the concepts of both systems under consideration based upon proven and existing technology. However, many components of large heat conservation systems are commonly custom made to the requirements of a specific installation. This is particularly true of large heat exchangers and large water source heat pumps. For these devices, significant improvement in overall system operation is possible through slight improvement in the operating efficiency so that the slight savings in original investment achieved by the incorporation of an "off-the-shelf", off-optimum design is seldom warranted. For these devices then, system operational data has been drawn from manufacturer design predictions rather than actual measured data.

If sufficiently attractive performance is found for these systems to warrant mass production of a design or series of designs, the required operational data would be generated during the system demonstration phase.

It is assumed for initial costing purposes that distribution piping will be insulated steel pipe laid in prefabricated concrete conduit. Such pipe is in service under similar conditions as those required here to prove acceptability. Lower cost piping technology is the subject of considerable attention over the past few years. The potential for direct burial of various polymer pipes, polymer-lined concrete pipe, and asbestos pipe, when fully developed, will result in significantly lowered system costs. This is an area where additional manufacturer data, while not mandatory, is eagerly sought.

The distributed heat pump strategy which provides heating, cooling and hot water services from a two-pipe system requires that to take advantage of the simultaneous demand for heating and cooling within the service area, the flow to the heat pump in the cooling mode must come from the cold (return) line. This presupposes a water pump in the heat pump system which can overcome the system pressure to reverse the normal water flow. Water source heat pumps incorporating reversing pumps are not available commercially to our knowledge. Development and testing of such devices would allow, for instance, low density areas in the heating mode to derive their energy directly from high density users in the cooling mode without the necessity of pumping energy from the nominal energy source, essentially allowing the system to operate as a host of interconnected minisystems.

Another area where additional testing is required is the operation of heat pumps in a low lift mode. Little if any information is available upon the operation of large water source heat pumps where the energy is pumped from 120°F source to 140°F or so (i.e., a lift of 20°F). Theoretically, the COP will approach infinity as the lift approaches zero. Under situations where waste heat is available at 120°F, the cost of a heat exchanger to deliver sufficient energy to air, and the ductwork modification (for central forced air conversion) may be very expensive. It is possible that considerable overall system savings could be effected by fairly low lift heat pumps for such cases.

For the central heat pump strategy, provision of space cooling is assumed to require a four-pipe system and increases overall system costs very significantly. Absorption chillers could perhaps

provide the cooling function from a two-pipe system. The temperature of the system water, at 140°F, is rather too low for existing absorption chilling systems to operate efficiently. Increasing the system water temperature causes an undesirable penalty in COP during the heating season. Development of low source temperature absorption chillers would enhance the central heat pump strategy where all three services are provided.

It is assumed that energy storage techniques are available for any desired quantity of low-grade energy. Simple steel tanks with 2 to 4 inches of urathene insulation are well known in fairly large sizes. Storage of the required volumes of hot water in aquifers or covered ponds appears to be a more cost-effective means. These concepts, however, are as yet to be tested on a large scale over the long term.

Waste water outfalls and warm water ejected to sewers represent significant energy sources. In some industrial cases, these water streams will also carry spent process chemicals of a more or less corrosive nature and/or biodegradable material. The effects of these residues upon heat exchanger surfaces will need to be measured, so that appropriate cleaning and/or replacement schedules can be devised. Advanced high efficiency heat exchangers and heat exchanger configurations/materials particularly resistant to fouling or corrosion would, if developed, improve the competitive position of HP-ICES strategies in general.

A final area where additional data is required concerns user devices and retrofit costs. Both central and distributed layouts require further effort here.

For the central case, it is assumed that a water-to-air heat exchanger can be installed in the ductwork of central forced-air type heating systems, i.e., in place of the existing furnace. By designing to achieve the same duct air temperatures as delivered by the existing furnace (as specified in Reference 9), no modification to the ductwork is required other than heat exchanger installation. Three or more passes are indicated for the water side. A variety of geometrical arrangements is possible, depending upon whether or not the consumer insists upon retaining his own system as a backup.

For the central heat pump layout, the means to heat potable water may follow European technology, i.e., a water-to-water heat exchanger. While available "off the shelf", from European manufacturers, data regarding the response of these devices using lower temperature district water supply (i.e., 140°F) is lacking.

For the distributed heat pump layout, the heat pump itself, as applied to space heating and cooling, is well defined with many manufacturers competing for the present market. The novelty of the system under investigation is that the temperature of the water source is significantly higher than the common well water heat source. Several advantages are projected to accrue from this difference. Primarily, a significant improvement in performance is predicted based upon well established thermodynamic relationships. While there is little question that such improved performance will be achieved in steady operation, the cyclic on-off operation required for demands less than the design demand will result in some decrease in performance coefficient. While confidence is high that this performance decrease will be slight, measured data from an actual system operating from a high temperature water source is desirable.

Secondary advantages foreseen from higher temperature water sources are longer life for the compressor and lower noise levels generated during its operation. These in turn will be felt as lower operation and maintenance costs and decreased first cost (from less sound insulation required). These advantages should be quantified.

For the distributed heat pump arrangement, devices to heat potable water are not currently available. One manufacturer has been located which produces an add-on water preheater for an air source heat pump. Essentially, this device acts to desuperheat the refrigerant, prior to the condenser, taking some of the load off the existing hot water heater. In this mode, questions concerning delivery of sufficient heat to provide both space and water demands are avoided. When the ambient air source is of low temperature, there is less superheat; and hence a greater fraction of the water heating demand is provided by the existing heating coil. While the existence of this water preheating device shows that health and safety requirements for refrigerant heated potable water can be met, its actual performance for a water source heat pump may not be suitable. It is likely that a separate condensing coil arranged to respond to the hot water demand independent of the space heating demand will show significantly better performance. Any ramifications of this design option upon the rest of the heat pump equipment needs to be identified.

It is possible that a small heat pump, devoted to hot domestic water production, could show advantages. Especially attractive would be one with the alternate capability to draw energy from district heating water or from room air. No manufacturer was found currently marketing such a device.

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APPENDIX A.0

MATHEMATICAL ANALYSIS

A.0 MATHEMATICAL ANALYSIS

The basic heat balance equations and the cost relations are presented in this section according to the structure of the corresponding ICES computer code.

This code was constructed within a research/development effort and, therefore, it is not designed to be a user oriented computer package.

A.1 USER DEMANDS

A.1.1 Averaged Daily Heating and Cooling Temperatures

Heating:

$$T = 65 - \frac{1}{24} \sum_{i=1}^{24} T_i^H$$
$$T_i^H = 0 \text{ if } T_i^H > 65 \quad (\text{A.1.1})$$

Cooling:

$$T_c = 65 + \frac{1}{24} \sum_{i=1}^{24} T_i^H$$
$$T_i^H = 0 \text{ if } T_i^H < 65 \quad (\text{A.1.2})$$

where:

- T_i^H = hourly dry bulb temperature
- T = averaged daily heating temperature
- T_c = averaged daily cooling temperature

A.1.2 Heating and Cooling Demands

Space heating demand per user:

$$\dot{q}_{SH} = 605.8 (T_{REF} - T) - 3,636$$

$$\text{if } (T_{REF} - T) > 6$$

$$\dot{q}_{SH} = 0$$

$$\text{if } (T_{REF} - T) \leq 6$$

(A.1.3)

Hot water heating demand per user:

$$\dot{q}_{HW} = 2,291$$

(A.1.4)

Space cooling demand per user:

$$\dot{q}_{SC} = 876.9 (T_C - T_{REF})$$

$$\text{if } (T_C - T_{REF}) > 9.5$$

$$\dot{q}_{SC} = 0$$

$$\text{if } (T_C - T_{REF}) \leq 9.5$$

(A.1.5)

Total demands:

$$\dot{Q}_{SH} = N \dot{q}_{SH}$$

$$\dot{Q}_{HW} = N \dot{q}_{HW}$$

$$\dot{Q}_{SC} = N \dot{q}_{SC}$$

$$\dot{Q} = \dot{Q}_{SH} + \dot{Q}_{HW}$$

(A.1.6)

where N is the number of users.

Design demand:

$$\dot{q}_{SH}^D = 605.8 (T_{REF} - T_{DSG}) - 3,636$$

$$\dot{q}_{HW}^D = 2,291$$

$$\dot{Q}_D = \dot{Q}_{SH}^D + \dot{Q}_{HW}^D \quad (A.1.7)$$

A.2 CENTRAL HEAT PUMP SYSTEM

A.2.1 Heating Mode Balance Equations

The mathematical model is depicted in Figure A-1, which is subdivided into four subsystems shown in Figure A-2. The calculation procedure follows the balance equations of the above subsystems.

Design conditions:

- Subsystem I

$$\dot{M}_D T_{1D} + \dot{W}_P = \dot{Q}_{TL} + \dot{M}_D T_{2D}$$

$$\dot{W}_P = k \dot{M}_D \Delta P / \eta_P$$

$$\dot{Q}_{TL} = K_T (T_{1D} - T_{soil}) \quad (A.2.1)$$

- Subsystem II

$$\dot{M}_D T_{2D} = \dot{Q}_D + \dot{M}_D T_{3D} \quad (A.2.2)$$

Operational conditions:

- User heat exchanger design

$$\Theta_1 = T_{2D} - T_{duct}$$

$$\Theta_2 = T_{3D} - T_{air}$$

$$T_M = (\Theta_1 - \Theta_2) / \ln (\Theta_1 / \Theta_2)$$

$$\zeta = \dot{q}_{SH}^D / T_M$$

$$C_H = \dot{M}_D / N$$

$$C_A = \dot{q}_{SH}^D / (T_{duct} - T_{air})$$

**MATHEMATICAL MODEL FOR THE CENTRAL HEAT PUMP SYSTEM
(HEATING MODE)**

**SUBSYSTEMS FOR THE CENTRAL HEAT PUMP SYSTEM
(HEATING MODE)**

$$C_{\min} = \text{Min} (C_H, C_A)$$

$$C_{\max} = \text{Max} (C_H, C_A)$$

$$\epsilon = \frac{1 - \text{Exp} \left[\left(\frac{AU}{C_{\min}} \right) \left(1 - C_{\min}/C_{\max} \right) \right]}{1 - \frac{C_{\min}}{C_{\max}} \text{Exp} \left[\left(-AU/C_{\min} \right) \left(1 - C_{\min}/C_{\max} \right) \right]} \quad (\text{A.2.3})$$

- Subsystem I

$$\dot{M}T_1 + \dot{W}_P = \dot{Q}_{TL} + \dot{M}T_2$$

$$\dot{W}_P = k \dot{M} \Delta P / \eta_P$$

$$\dot{Q}_{TL} = K_T (T_1 - T_{\text{soil}})$$

$$\dot{M} = \frac{C_H}{\epsilon C_{\min}} \frac{\dot{Q}_{SH}}{T_2 - T_{\text{air}}} + \frac{\dot{Q}_{HW}}{(T_2 - T_W)} \quad (\text{A.2.4})$$

- Subsystem II

$$\dot{M}T_2 = \dot{Q} + \dot{M}T_3 \quad (\text{A.2.5})$$

- Subsystem III

$$\dot{M}T_3 + \dot{W}_P = \dot{Q}_{RL} + \dot{M}T_4$$

$$\dot{W}_P = k \dot{M} \Delta P / \eta_P$$

$$\dot{Q}_{RL} = K_R (T_3 - T_{\text{soil}}) \quad (\text{A.2.6})$$

- Subsystem IV

$$\dot{Q}_C + \frac{ds}{dt} + \dot{Q}_T + \dot{M}T_4 = \dot{M}T_1 \quad (\text{A.2.7})$$

A.2.2 Cooling Mode Balance Equations

The mathematical models are depicted in Figures A-3 and A-4.

- Subsystem I

$$T_2 \dot{M} + \dot{Q}_{SC} = \dot{M}T_3$$

$$T_3 - T_2 = \Delta \quad (\text{A.2.8})$$

**MATHEMATICAL MODEL FOR THE CENTRAL HEAT PUMP SYSTEM
(COOLING MODE)**

**SUBSYSTEMS FOR THE CENTRAL HEAT PUMP SYSTEM
(COOLING MODE)**

- Subsystem II

$$\dot{M}T_1 + \dot{W}_P = \dot{Q}_{TL} + \dot{M}T_2$$

$$\dot{W}_P = k \dot{M} \Delta P / \eta_P$$

$$\dot{Q}_{TL} = K_T (T_1 - T_{soil}) \quad (A.2.9)$$

- Subsystem III

$$\dot{M}T_3 + \dot{W}_P = \dot{M}T_4 + \dot{Q}_{RL}$$

$$\dot{W}_P = k \dot{M} \Delta P / \eta_P$$

$$\dot{Q}_{RL} = K_R (T_3 - T_{soil}) \quad (A.2.10)$$

- Subsystem IV

$$\dot{M}T_4 = \dot{Q}_{EV} + \dot{M}T_1 \quad (A.2.11)$$

A.2.3 Energy Calculations

- Heating mode

$$E_C = \oint \dot{Q}_C$$

$$E_{ST} = \oint ds/dt$$

$$E_T = \oint \dot{Q}_T$$

$$E_{TL} = \oint \dot{Q}_{TL}$$

$$E_{RL} = \oint \dot{Q}_{RL}$$

$$E_P = 2 \oint \dot{W}_P$$

$$E_V = \oint \dot{Q}$$

$$E_S = \oint \dot{M} (T_1 - T_4)$$

$$E_M = \oint \dot{Q}_C / COP$$

$$E_{EV} \equiv E_C - E_M$$

$$E_L = E_{TL} + E_{RL} \quad (A.2.12)$$

From the balance equations for Subsystems I through IV, one obtains the overall balance equation for the mathematical model of Figure A-2,

$$\dot{Q}_C + \frac{dS}{dt} + \dot{Q}_T + 2\dot{W}_P = \dot{Q}_{TL} + \dot{Q}_{RL} + \dot{Q} \quad (\text{A.2.13})$$

which yields the overall energy balance equation

$$E_C + E_{ST} + E_T + E_P = E_L + E_U \quad (\text{A.2.14})$$

- Cooling mode

$$E_{EV} = \phi \dot{Q}_{EV}$$

$$E_U = \phi \dot{Q}_{SC}$$

$$E_C = \phi \dot{Q}_{EV} \frac{1}{1 - 1/\text{COP}}$$

$$E_M = E_C - E_{EV} \quad (\text{A.2.15})$$

A.2.4 Heat Loss Estimation

For heat loss estimate, consider the energy balance equation (A.2.13) in the following form:

$$E_S + E_P = E_{TL} + E_{RL} + E_U \quad (\text{A.2.16})$$

where

$$E_S = E_C + E_{ST} + E_T \quad (\text{A.2.17})$$

Define,

$$E_L \equiv r E_U$$

$$a \equiv \frac{E_{RL}}{E_{TL}} \quad (\text{A.2.18})$$

Thus,

$$E_{TL} = \frac{r}{1+a} E_U$$

$$E_{RL} = \frac{ar}{1+a} E_U \quad (\text{A.2.19})$$

where the total energies per year are based on the design conditions, that is,

$$\begin{aligned} \dot{Q}_{TL} &= K_T (T_{1D} - T_{\text{soil}}) \\ \dot{Q}_{RL} &= K_R (T_{3D} - T_{\text{soil}}) \end{aligned} \quad (\text{A.2.20})$$

so that

$$\begin{aligned} E_{TL} &= K_T N (T_{1D} - T_{\text{soil}}) \\ E_{RL} &= K_R N (T_{3D} - T_{\text{soil}}) \end{aligned} \quad (\text{A.2.21})$$

Then, the substitution of equations (A.2.19) into (A.2.21) yields

$$\begin{aligned} K_T &= \frac{r a E_U}{(1+a) N} \frac{1}{(T_{3D} - T_{\text{soil}})} \\ K_R &= \frac{r a E_U}{(1+a) N} \frac{1}{(T_{3D} - T_{\text{soil}})} \end{aligned} \quad (\text{A.2.22})$$

where E_U/N may be estimated in terms of the design power as follows:

$$\begin{aligned} \frac{E_U}{N} &= \frac{\dot{Q}_D}{\beta} \\ \beta &\approx 3 \end{aligned} \quad (\text{A.2.23})$$

Thus,

$$\begin{aligned} K_T &= \frac{r}{1+a} \frac{\dot{Q}_D}{\beta} \frac{1}{T_{1D} - T_{\text{soil}}} \\ K_R &= \frac{r a}{1+a} \frac{\dot{Q}_D}{\beta} \frac{1}{T_{3D} - T_{\text{soil}}} \end{aligned} \quad (\text{A.2.24})$$

Assuming now that

$$\frac{K_T}{\dot{Q}_D} \approx \frac{K_R}{\dot{Q}_D} = \left[\frac{\hat{K}}{\dot{Q}_D} \right] \quad (\text{A.2.25})$$

where “a” refers to a system for which experimental data are available for heat losses, one obtains

$$r = \frac{1+a}{1+\hat{a}} \frac{T_{1D} - T_{soil}}{\hat{T}_{1D} - \hat{T}_{soil}} \hat{r}$$

$$a = \frac{T_{3D} - T_{soil}}{T_{1D} - T_{soil}}$$

$$\hat{a} = \frac{\hat{T}_{3D} - \hat{T}_{soil}}{\hat{T}_{1D} - \hat{T}_{soil}} \quad (A.2.26)$$

A.2.5 Topping, Storage, and Seasonal Operation

The balance equation for Subsystem IV,

$$Q_C + \frac{dS}{dt} + \dot{Q}_T + \dot{M}T_4 = \dot{M}T_1 \quad (A.2.27)$$

is solved for $\dot{Q}_C$, subject to the following constraints,

$$\dot{Q}_C \leq \dot{Q}_M$$

$$0 \leq S \leq S_{max}$$

$$S_I = (T_{1D} - T_{3D}) k V_I$$

$$S_M = (T_{1D} - T_{3D}) k V_M \quad (A.2.28)$$

such that $\dot{Q}_T$ is minimum and $\dot{Q}_C$ is that of local maximum.

In order to effect seasonal operation, the constraint $\dot{Q}_M$ is defined in terms of the maximum heat pump capacity $\dot{Q}_{max}$ according to a four season schedule shown below:

$$\dot{Q}_M = S_1 \dot{Q}_S \quad 1 \text{ to } 91 \text{ days}$$

$$\dot{Q}_M = \left(S_1 + \frac{S_3 - S_1}{n} m \right) \dot{Q}_S \quad 92 \leq m \leq 183$$

$$\dot{Q}_M = S_3 \dot{Q}_S \quad 184 \text{ to } 275 \text{ days}$$

$$\dot{Q}_M = \left(S_3 + \frac{S_1 - S_3}{n} m \right) \dot{Q}_S \quad 276 \leq m \leq 365$$

$$n = 91 \quad (A.2.29)$$

Weekly variations for all four seasons are effects as follows:

$$\begin{aligned}\dot{Q}_S &= w_i \dot{Q}_{\max} \\ i &= 1, 2, \dots, 7\end{aligned}\tag{A.2.30}$$

A.2.6 Solution Procedure for the Heating Mode

The following quantities are defined a priori:

- Temperatures

$$T_1(0), T_3(0), T_{\text{soil}}, T_{\text{ref}}, T_{\text{dsg}}, T_{\text{air}}, T_{\text{duct}}, T_w\tag{A.2.31}$$

- Pressure and pump efficiency

$$\Delta P, \eta_p\tag{A.2.32}$$

- Maximum heat pump capacity

$$\dot{Q}_{\max}\tag{A.2.33}$$

- Heat loss factor and design temperatures for a known system

$$\hat{T}_{1D}, \hat{T}_{3D}, \hat{T}_{\text{soil}}, \hat{r}\tag{A.2.34}$$

- Storage tank data

$$V_I, V_{\max}\tag{A.2.35}$$

- Seasonal and weekly schedule

$$\begin{aligned}S_1, S_3 \\ w_1, w_2, \dots, w_7\end{aligned}\tag{A.2.36}$$

The solution procedure then follows the balance equations of Subsystems I through IV. A step-by-step breakdown is given below.

- Step 1: Set up averaged daily temperatures (Section A.1.1)
- Step 2: Establish demands (Section A.1.2)
- Step 3: Estimate heat loss factors (Section A.2.4)

- Step 4: Solve equations (A.2.1) through (A.2.3) for T_{2D} , T_{3D} , and $\dot{M}_D$.
- Step 5: Solve equations (A.2.4) for $\dot{M}$ and T_2 .
- Step 6: Solve equation (A.2.5) for T_3 .
- Step 7: Solve equation (A.2.6) for T_4 .
- Step 8: Establish topping, storage, and seasonal characteristics (Section A.2.5)
- Step 9: Calculate yearly energy consumptions (Section A.2.3).

The above steps will be reiterated in the discussion of the computer program flow chart, Section A.7.

A.2.7 Solution Procedure for the Cooling Mode

In addition to the prescribed quantities of Section A.2.6, the temperature drop across the user heat exchanger, Δ is defined a priori.

The calculation procedure is as follows:

- Step 1: Solve equation (A.2.8) for $\dot{M}$
- Step 2: Solve equations (A.2.9) for T_2
- Step 3: Solve equations (A.2.10) for T_4
- Step 4: Solve equation (A.2.11) for $\dot{Q}_{TV}$
- Step 5: Calculate yearly energy consumptions (Section A.2.3)

A.3 DISTRIBUTED HEAT PUMP SYSTEM

A.3.1 Heating Mode Balance Equations

The mathematical model is shown in Figure A-5, which is subdivided into five subsystems shown in Figure A-6. The calculation procedure follows the balance equations of the above subsystems.

Design Conditions

- Subsystem I

$$\dot{M}_D T_{1D} + \dot{W}_P = \dot{Q}_{TL} + \dot{M}_D T_{2D}$$

$$\dot{W}_P = k \dot{M}_D \Delta P / \eta_P$$

$$\dot{Q}_{TL} = K_T (T_{1D} - T_{soil}) \quad (A.3.1)$$

- Subsystem II

$$\dot{M} T_{2D} = \dot{Q}_{ED} + \dot{M} T_{3D}$$

**MATHEMATICAL MODEL FOR THE DISTRIBUTED HEAT PUMP SYSTEM
(HEATING MODE)**

**SUBSYSTEMS FOR THE DISTRIBUTED HEAT PUMP SYSTEM
(HEATING MODE)**

$$\dot{Q}_{ED} = \frac{C_D - 1}{C_D} \dot{Q}_D$$

$$C_D = a + b T_{3D}$$

$$\Delta T_R = T_{2D} - T_{3D} \quad (A.3.2)$$

Operational Conditions

- Subsystem I

$$\dot{M}T_1 + \dot{W}_P = \dot{Q}_{TL} + \dot{M}T_2$$

$$\dot{W}_P = k \dot{M} \Delta P / \eta_P$$

$$\dot{Q}_{TL} = K_T (T_1 - T_{soil}) \quad (A.3.3)$$

- Subsystem II

$$\dot{M}T_2 = \dot{Q}_E + \dot{M}T_3$$

$$\dot{Q}_E = \frac{c - 1}{c} \dot{Q}$$

$$\Delta T_H = T_2 - T_3$$

$$c = a + b T_3$$

$$\dot{Q} \leq \dot{Q}_{max} \quad (A.3.4)$$

- Subsystem III

$$\dot{M}T_3 + \dot{W}_P = \dot{Q}_{RL} + \dot{M}T_4$$

$$\dot{W}_P = k \dot{M} \Delta P / \eta_P$$

$$\dot{Q}_{RL} = K_R (T_3 - T_{soil}) \quad (A.3.5)$$

- Subsystem IV

In order to effect seasonal operation, equations (A.2.27) through (A.2.30) are formally utilized, where $\dot{Q}_C$ is interpreted as the seasonal power available in the distribution stream.

- Subsystem V

$$\dot{Q} = \dot{Q}_C + \dot{Q}_B$$

$$\dot{Q}_C = \frac{c}{c-1} \dot{Q}_E$$

$$C = a + b T_3 \quad (A.3.6)$$

where $\dot{Q}_B$ refers to the local electrical backup

A.3.2 Cooling Mode Balance Equations

In the cooling mode, the balance equations for Subsystems II are modified as follows:

- Subsystem II

$$\dot{M}T_2 + \dot{Q}_C = \dot{M}T_3$$

$$\dot{Q}_C = \dot{Q}_{SC} \frac{c}{c-1}$$

$$c = a + b T_3$$

$$\Delta T_C = T_3 - T_2$$

$$\dot{Q}_{SC} \leq \left(1 - \frac{1}{C}\right) \dot{Q}_{\max} \quad (A.3.7)$$

A.3.3 Simultaneous Heating and Cooling

The basic balance equations are those of Sections A.3.1 and A.3.2. In addition, the reversal cooling pump power is defined as

$$\dot{W}_{CP} = k \Delta P [M]_c / \eta_p \quad (A.3.8)$$

A.3.4 Energy Calculations

- Heating mode
Equations (A.2.12) through (A.2.14)
- Cooling mode
Equations (A.2.15)

- **Simultaneous Heating and Cooling**

In addition to the above yearly energy usage, the differential heating and cooling stream energy is calculated as follows:

$$E_{PD} = \phi a (\dot{M}_H - \dot{M}_C) \Delta T_H \quad (A.3.9)$$

where:

$$a = 1 \text{ if } (\dot{M}_H - \dot{M}_C) > 0$$

$$a = 0 \text{ if } (\dot{M}_H - \dot{M}_C) \leq 0$$

A.3.5 Solution Procedure

In addition to the quantities defined in Section A.2.6, the temperature differentials ΔT_H and ΔT_C are prescribed a priori in equations (A.3.1) through (A.3.7).

The solution procedure follows the outline of Sections A.2.6 and A.2.7.

A.4 CAPITAL INVESTMENTS

The capital expenditures are established by the data provided in References 3, 13, 17, and 19.

A.4.1 Central Heat Pump System

- **Distribution cost**

$$C_{distr} = a 760 \frac{N}{\sqrt{N_G}} \frac{\dot{q}_D}{\sqrt{T_{1D} - T_{3D}}} \left[1 + \frac{95.41}{\sqrt{\frac{N_N}{N_G}}} \left(\frac{T_{1D} - T_{3D}}{\dot{q}_D} \right)^{0.4} \right] \quad (A.4.1)$$

(Adopted from Reference 19)

where

$$a = 1.72 \text{ for simultaneous heating and cooling.}$$

- **Storage cost**

$$C_{store} = 1.2 \left(27.258 V_{max}^{0.3} + 2.8725 V_{max}^{0.666} \right) \quad (A.4.2)$$

(From Reference 13)

- **Boiler cost**

$$C_{boiler} = 0.689145 \dot{Q}_D^{0.72} \quad (A.4.3)$$

(From Reference 13)

- Heat exchanger cost

$$C_{\text{heate}} = N \left[\frac{0.1}{T_M} \dot{q}_D + 100 a \right] \quad (\text{A.4.4})$$

(From Reference 13)

where

$$a = 0 \text{ if hot water is not included}$$

$$a = 1 \text{ if hot water is included}$$

and

$$T_M = (\Theta_1 - \Theta_2) / \ln \left(\frac{\Theta_1}{\Theta_2} \right)$$

$$\Theta_1 = T_{1D} - T_{\text{duct}}$$

$$\Theta_2 = T_{3D} - T_{\text{air}}$$

- Heat pump cost

$$C_{\text{heat p}} = 1.5 \ddot{Q}_D \left[-1.8667 \times 10^{-6} T_{1D} T_{W3} + 1.5233 \times 10^{-4} T_{W3} + 2.518 \times 10^{-4} T_{1D} - 0.018585 \right] \quad (\text{A.4.5})$$

(Adopted from Reference 17)

- Transmission pipeline cost

$$C_{\text{t pline}} = [2 (0.1289) D^{1.88}] L$$

(From Reference 3)

- Total hardware cost

$$C_{\text{total}} = C_{\text{distr}} + 2C_{\text{store}} + C_{\text{boiler}} + C_{\text{heate}} + C_{\text{heatp}} \quad (\text{A.4.7})$$

$$C_{\text{total}}^* = C_{\text{total}} + 100 N a \quad (\text{A.4.8})$$

where

$$a = 0 \text{ if hot water is not included}$$

$$a = 1 \text{ if hot water is included}$$

Adding the transmission pipeline cost and 15% miscellaneous cost, the total investment cost is

$$C_{\text{total}}^{**} = 1.15 C_{\text{total}}^* + C_{\text{t pline}} \quad (\text{A.4.9})$$

A.4.2 Distributed Heat Pump System

- Distribution cost

$$C_{\text{distr}} = 760 \frac{N}{\sqrt{N_G}} \sqrt{\frac{A}{T_{1D} - T_{3D}}} \left[1 + \frac{95.41}{\sqrt{\frac{N_N}{N_G}}} \left(\frac{T_{1D} - T_{3D}}{A} \right)^{0.4} \right] \quad (\text{A.4.10})$$

(Adopted from Reference 19)

where

$$A = \frac{c-1}{c} \dot{q}_D$$

- Storage cost

$$C_{\text{store}} = 1.2 \left(27.258 V_{\text{max}}^{0.3} + 2.8725 V_{\text{max}}^{0.666} \right) \quad (\text{A.4.11})$$

(From Reference 13)

- Boiler cost

$$C_{\text{boiler}} = 0.689145 A^{0.72} \quad (\text{A.4.12})$$

(From Reference 13)

where

$$A = \frac{c-1}{c} \dot{Q}_D$$

- Heat exchanger cost

$$C_{\text{heate}} = N [823.440.375 \dot{q}_D] \quad (\text{A.4.13})$$

(From Reference 13)

- Heat pump cost

$$C_{\text{heat p}} = N [100 + (\dot{q}_{\text{SH}} + \dot{q}_{\text{HW}})/10 T_M] \quad (\text{A.4.14})$$

(From Reference 17)

- Transmission pipeline cost

$$C_{\text{tpline}} = [2 (0.1289) D^{1.88}] L \quad (\text{A.4.15})$$

(From Reference 3)

- Total hardware cost

$$C_{\text{total}} = C_{\text{distr}} + C_{\text{store}} + C_{\text{boiler}} + C_{\text{heate}} + C_{\text{heatp}} \quad (\text{A.4.16})$$

$$C_{\text{total}}^* = C_{\text{total}} + 100 N \alpha \quad (\text{A.4.17})$$

where

$a = 0$ if hot water is not included

$a = 1$ if hot water is included

Adding the transmission pipeline cost and 15% miscellaneous cost, the total investment cost is

$$C_{\text{total}}^{**} = 1.15 C_{\text{total}}^* + C_{\text{tpline}} \quad (\text{A.4.18})$$

A.5 ENERGY COST

- Topping fuel cost

$$F_T = a_F E_T / (a_H \eta_B) \quad (\text{A.5.1})$$

- Electrical energy cost

$$F_E = \frac{a_E}{3,412} (E_M + E_P)$$

$$F_B = \frac{a_E}{3,412} E_B \quad (\text{A.5.2})$$

where

$a_F = 0.4$ dollar/gallon

$a_E = 0.04$ dollar/KWH

$a_H = 140,000$ gallon/Btu (A.5.3)

A.6 LIFE CYCLE COST ANALYSIS

The life cycle cost analysis is discussed in Section 9.4.

A.7 FLOW CHART OF THE ICES COMPUTER CODE

A.8 OUTPUT NOMENCLATURE

The energy and cost related items are summarized here according to the computer output format.

A.8.1 Central Heat Pump System With Simultaneous Heating and Cooling

- Heat loss considerations

Loss factor	r	
Transmission loss	E_{TL}	
Return loss	E_{RL}	
Total line loss	E_L	
Energy supplied to user	E_U	
Source energy usage	E_S	
Pump energy usage	E_P	
Error	δ	
Initial store energy	S_I	
Final store energy	S_{max}	(A.8.1)

Set (A.8.1) refers to the heating mode. The following energy balance applies:

$$E_S + E_P = E_U + E_L \quad (A.8.2)$$

Cooling energy considerations

Source energy usage	E_S	
Cooling user demand	E_U	
Condenser energy	E_C	
Compressor energy	E_M	
Pump energy	E_P	
Total line loss	E_L	(A.8.3)

The following energy balance applies

$$E_S + E_P = E_U + E_L$$
$$E_C = E_M + E_U \quad (A.8.4)$$

The following quantities enter in the life cycle cost analysis:

Total user demand	$(E_U)_H + (E_U)_C$
Total compressor energy	$(E_M)_H + (E_M)_C$
Total pump energy	$(E_P)_H + (E_P)_C$

(A.8.5)

- Power and energy considerations

Source energy usage	E_S
Topping	E_T
Drawing	E_{ST}^-
Filling	E_{ST}^+
Initial storage energy	S_I
Final store energy	S_F
Condenser	E_C
Compressor energy usage	E_M
Evaporator energy usage	E_{EV}
Usage	E_U

(A.8.6)

Set (A.8.6) refers to the heating mode. The following energy balance applies:

$$E_S = E_C + E_{ST}^+ - E_{ST}^- + S_F - S_I + E_T$$

$$E_C = E_{EV} + E_M$$

(A.8.7)

- Operation costs

Cost of electricity a_E

Cost of fuel a_F

Fuel heating valve a_H

Boiler efficiency η_B

Water pump efficiency η_P

Heat pump operational cost F_E

Topping fuel cost F_B

(A.8.8)

The heat pump operation cost, F_E , is based on the total compressor and pump energies defined in set (A.8.5).

- Capital investments

Total distribution cost C_{distr}

Total storage cost C_{store}

Topping boiler cost C_{boiler}

Central heat pump cost C_{hpump}

Total hardware cost	C_{total}^*
Transmission pipeline cost	$C_{tp\text{live}}$
Total investment cost	C_t^{**}

(A.8.9)

A.8.2 Distributed Heat Pump System With Simultaneous Heating and Cooling

• Heat loss considerations

Loss factor	r
Transmission loss	E_{TL}
Return loss	E_{RL}
Total line loss	E_L
Energy supplied to user	E_U
Source energy usage	E_S
Pump energy usage	E_P
Local topping	E_B
Evaporator energy usage	E_{EV}
Compressor energy usage	E_M

(A.8.10)

Set (A.8.10) refers to the cooling mode. The following energy balance applies:

$$E_S + E_P = E_{EV} + E_L$$

(A.8.11)

$$E_U = E_{EV} + E_M + E_B$$

Simultaneous heating and cooling

Heating energy supplied to user	$(E_V)_H$
Cooling energy supplied to user	$(E_U)_C$
Total energy supplied to user	$(E_U)_H + (E_U)_C$
Cooling compressor energy	$(E_M)_G$
Energy due to pstv mass flw dif	E_{PD}

(A.8.12)

The following quantities enter in the life cycle cost analysis:

Total user demand	$(EU)_H + (EU)_C$	
Total compressor energy	$(EM)_H + (EM)_C$	
Total pump energy	E_M	(A.8.13)

- Power and energy considerations

Source energy usage	E_S	
Topping	E_T	
Drawing	$\bar{E}_{ST}$	
Filling	E_{ST}^+	
Initial store energy	S_I	
Final store energy	S_F	
Heat pump usage	E_C	
Compressor	E_M	
Evaporator energy usage	E_{EV}	
Usage	E_U	(A.8.14)

Set (A.8.14) applies to the heating mode. The interpretation of E_C is given in Section (A.3).

The following energy balance applies:

$$E_C + E_T + E_{ST}^+ - \bar{E}_{ST} + S_F - S_I = E_S$$

$$E_{EV} + E_M = E_U \quad (A.8.15)$$

- Operational costs

Heat pump operational cost	F_E	
Topping fuel cost	F_B	(A.8.16)

The heat pump operation cost, F_E , is based on the total compressor and pump energies defined in set (A.8.13).

- Capital investments

Total distribution cost	C_{distr}
Total storage cost	C_{store}
Topping boiler cost	C_{boiler}
Total heat pump cost per user	C_{hpump}/N
Total heat exchanger cost	C_{heate}
Cooling pump cost	C_{clpmp}
Total hardware cost	C_t^*
Transmission pipe line cost	C_{pline}
Total investment cost	C_t^{**}

NOMENCLATURE

Power Related Symbols

$\dot{q}_{SH}$	=	Space heating demand per user (Btu/hr)
$\dot{q}_{SC}$	=	Space cooling demand per user (Btu/hr)
$\dot{q}_{HW}$	=	Hot water heating demand per user (Btu/hr)
$\dot{Q}_{SH}$	=	Space heating demand (Btu/hr)
$\dot{Q}_{SC}$	=	Space cooling demand (Btu/hr)
$\dot{Q}_{HW}$	=	Hot water heating demand (Btu/hr)
$\dot{Q}_C$	=	Condenser power (Btu/hr)
$\dot{Q}_{TL}$	=	Transmission line loss (Btu/hr)
$\dot{Q}_{RL}$	=	Return line loss (Btu/hr)
$\dot{Q}_T$	=	Rate of topping (Btu/hr)
$\frac{dS}{dt}$	=	Storage rate (Btu/hr)
$\dot{Q}_{EV}$	=	Evaporator power (Btu/hr)
$\dot{Q}$	=	Energy rate delivered to the user (Btu/hr)
$\dot{Q}_{max}$	=	Maximum heat pump power (Btu/hr)
$\dot{W}_P$	=	Pump power (Btu/hr)

Energy Related Symbols

E_C	=	Condenser energy requirement (Btu/year)
E_{ST}	=	Energy drawn from storage (Btu/year)
E_T	=	Energy supplied by topping (Btu/year)
E_{TL}	=	Transmission line energy loss (Btu/year)

NOMENCLATURE (Continued)

E_{RL}	=	Return line energy loss (Btu/year)
E_p	=	Pump energy requirement (Btu/year)
E_U	=	Energy delivered to the user (Btu/year)
E_S	=	Source energy requirement (Btu/year)
E_M	=	Compressor energy requirement (Btu/year)
E_{EV}	=	Evaporator energy usage (Btu/year)
E_L	=	Total line loss (Btu/year)
M	=	Flow rate (lbs/hr)

Temperatures

T_1	=	Transmission line inlet temperature
T_2	=	Transmission line outlet temperature
T_3	=	Return line inlet temperature
T_4	=	Return line outlet temperature
T_{soil}	=	Soil temperature
T_{ref}	=	Reference temperature
T_i^H	=	Hourly dry bulb temperature
T	=	Average daily heating temperature
T_C	=	Average daily cooling temperature
T_{duct}	=	Duct temperature
T_{air}	=	Air temperature
T_w	=	Water inlet temperature to hot water tank

NOMENCLATURE (Continued)

Cost Related Symbols

C_{distr}	=	Distribution system cost (dollars)
C_{store}	=	Storage tank cost (dollars)
C_{boiler}	=	Boiler cost (dollars)
C_{heate}	=	Heat exchanger cost (dollars)
C_{heatp}	=	Heat pump cost (dollars)
C_{tpline}	=	Transmission pipeline cost (dollars)
F_T	=	Topping fuel cost (dollars/year)
F_E	=	Electrical energy cost (dollars/year)
F_B	=	Boiler fuel cost (dollars/year)
a_F	=	Topping fuel cost (dollars/gallon)
a_E	=	Cost of electricity (dollars/KWH)
a_H	=	Fuel heating value (gallon/Btu)

Storage Tank

S_I	=	Initial storage energy (Btu)
S_M	=	Maximum storage energy (Btu)
V_I	=	Initial effective storage volume (gallons)
V_{max}	=	Maximum storage tank volume (gallons)

Miscellaneous Symbols

N	=	Number of users
N_G	=	Number of users per gross square mile
N_N	=	Number of users per net square mile

NOMENCLATURE (Concluded)

η_P	=	Pump efficiency
η_B	=	Topping boiler efficiency
c	=	Heat pump coefficient of performance
ΔP	=	Pressure drop across line pumps (psi)
k	=	Conversion factor
ϵ	=	Heat exchanger effectiveness
D	=	Pipeline diameter (inch)
L	=	Pipeline length

APPENDIX B
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