U.S. Department of Housing and Urban Development
Office of Policy Development and Research

USE OF DUCTLESS MINI-SPLIT ELECTRIC HEAT PUMPS IN RESIDENCES

Phase I
Review and Assessment

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IN RESIDENCES

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EXECUTIVE SUMMARY

This report addresses the use of ductless electric heat pumps for heating and air conditioning of new homes. Specific objectives include the following:

1. To provide information on the types and intended applications of currently available ductless systems.

2. To provide information on the initial, operating, and installation costs of currently available equipment.

3. Where appropriate, to provide recommendations to manufacturers for improving ductless equipment and lowering initial costs.

4. If applicable, to gain insight into practical field problems through installation and demonstration of a ductless system in a new home.

BACKGROUND

Currently, the most widely used residential HVAC system is the forced-air system, which relies on ducts to distribute conditioned air throughout the house. Ductless systems, as their name implies, do not use ducts. Instead, small-diameter refrigerant lines run from an outdoor compressor to an air handler located in each zone or room. Typically, only minor losses are associated with the distribution system of a ductless unit. Conversely, the ducts used with forced-air distribution systems have been identified as an important contributor to energy losses in residential buildings in terms of both air leakage and conduction.

A conventional ducted forced-air system typically has a single indoor unit and a single outdoor unit. A ductless system uses an individual indoor unit in each room or zone. Depending on the house layout, a ductless system may require multiple outdoor units, which increases costs. Heating and cooling design capacities can be reduced when each zone has its own thermostat that can respond to changes in solar and/or internal loads. The thermostat setting in each room or zone can be easily set back in the heating mode and set up in the cooling mode according to the use of each zone. Equipment can also be turned on/off conveniently depending on the use of the zone. Initial installation costs may also be reduced through zoning.

Potential benefits of ductless systems include elimination of ductwork, simplified installation, and energy savings. These benefits can potentially reduce HVAC costs through lower first costs or reduced operating costs.

CURRENTLY AVAILABLE PRODUCTS

Dozens of ductless systems of various capacities and configurations were identified during this project.

Most indoor units are either mounted directly to the wall or rest on the floor and are highly visible. Many systems are outfitted with expensive plastic extrusions and trim that, while meeting certain discriminating requirements for office space, give the units an institutional appearance. Home owners are likely to find ductless units aesthetically unappealing, at least until the units can be completely recessed into the wall or even into a closet.

Nearly all of the units have been designed to serve offices and other areas that have considerably higher demand loads than individual rooms in most homes. As such, many systems have the capacity to serve an entire home. Even some single-zone systems could serve a small entry-level home were they not designed for a single-room application.

COST EVALUATION

A sample 1,200 square foot home was used to compare costs of a ductless system to a forced-air ducted system. It appears that some ductless heat pumps can be cost-competitive with ducted heat pumps from both first cost and life-cycle perspective. This is, however, highly dependent on the specific equipment and number of zones within a home.

DEMONSTRATION HOME

To evaluate the performance and installation of a ductless system, a demonstration home will be constructed in Phase II of this project. Both a conventional heat pump system and a ductless system will be installed in the demonstration home. Energy use and comfort will be monitored for comparison of the two systems over one summer and one winter.

RECOMMENDATIONS

Recommendations to lower costs of ductless systems based on the information collected under this project include:

- *Modify ductless units to permit their installation in walls or ceilings and to allow the units to serve two or more rooms with similar time-demand patterns.* If a single unit could serve more than one room, the number of units could be decreased to create a better match between loads and units.

- *Develop systems that will run multiple indoor units on one compressor.* Currently, many indoor units are matched to their own compressors, i.e., three indoor units require three outdoor compressors. Reducing the number of compressors should decrease the cost of ductless systems.

- *Eliminate nonessential components.* Many currently available ductless units feature advanced electronic controls that increase the cost of the systems. By simplifying the electronic controls, the cost of the units will decrease.

- *Modify the housings used on indoor units.* Many ductless units use expensive plastic housings that could be replaced by less expensive types of plastic or metal.

- *Examine hybrid systems.* A combination system that combines ductless systems with parts of the ducted system may be the most cost-effective system. It may be possible to install short lengths of duct from currently operating indoor units to an adjacent room or zone.

CONCLUSIONS

Ductless systems may have the capability to be more energy efficient than conventional systems. They offer an easy method of zonal distribution in a house. Ductless systems also permit home owners to set their own operating schedules by controlling set up and set back strategies within different house zones.

From a first cost standpoint, the use of ductless systems in their present form may be justified in some new construction depending on the house layout and number of zones. The cost of ductless systems will, however, decrease as demand increases, and sales will increase if ductless system manufacturers create and market a ductless system that is compatible with home construction. Phase II of this project calls for NAHB Research Center personnel to work with manufacturers to develop and test lower-cost systems.

INTRODUCTION

This report is part of a program funded by the U.S. Department of Housing and Urban Development (HUD) to investigate technologies and materials that can potentially enhance housing affordability. Specifically, this report addresses the use of ductless electric heat pumps for heating and air conditioning.

Currently, the most widely used residential HVAC system is the forced-air system, which relies on ducts to distribute conditioned air throughout the house. Ductless systems, as their name implies, do not use ducts. Instead, small-diameter refrigerant lines run from an outdoor compressor to an air handler located in each zone or room (Figure 1). Ductless heat pump systems (ductless systems) may provide a way to condition air in a home at a lower or equivalent cost than forced-air systems while improving or providing acceptable comfort. Potential benefits include the following:

1. Elimination of ductwork--Duct installation is one of the more labor-intensive activities associated with a forced-air system. In addition, ducts frequently occupy space that could otherwise be used as living space.

2. Simplified installation--Refrigerant lines can be placed in any wall or floor without special chases. The absence of chases reduces the need for additional framing or bulkheads that are often required where ducts pass through living space.

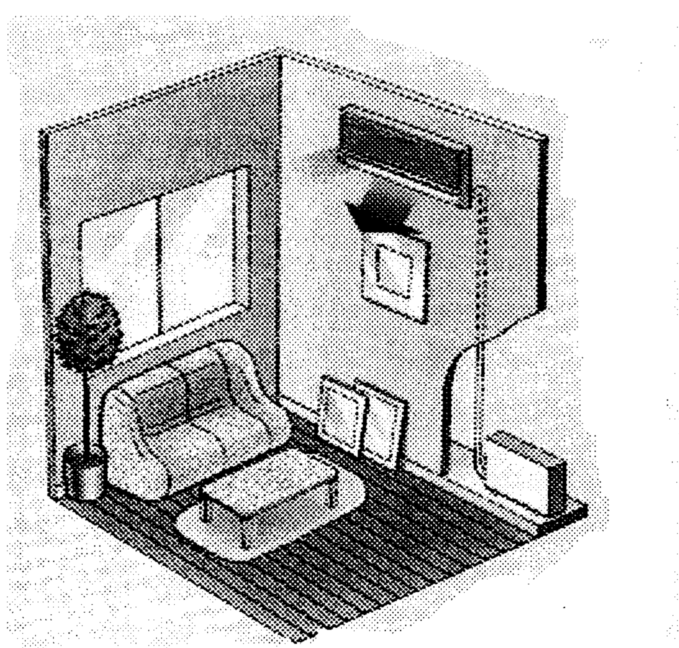

Figure 1. Typical Ductless Heat Pump System
Courtesy of Sanyo Fisher Corporation

3. Energy savings--Refrigerant lines are expected to experience considerably smaller thermal losses than ducts and to eliminate the air leakage associated with ducts. Ductless systems are also designed for zoned application, which can further increase energy savings and comfort.

These benefits can potentially reduce HVAC costs through lower first costs or reduced operating costs. Nonetheless, there are several potential barriers to the widespread use of ductless systems. The most notable barriers may include higher equipment costs, problems of home owner acceptance, and a lack of equipment compatible with residential applications in the United States.

This project addresses the potential benefits of ductless systems in homes and considers methods for reducing barriers to their use. Specific objectives include the following:

1. To provide information on the types and intended applications of currently available ductless systems.

2. To provide information on the equipment, operating, and installation costs of currently available systems.

3. Where appropriate, to provide recommendations to manufacturers for improving ductless equipment and lowering initial costs.

4. If applicable, to gain insight into practical field problems through installation and demonstration of a ductless system in a new home.

This Phase I report, Review and Analysis, covers objectives 1, 2, 3 and the design and planning for objective 4. The demonstration of a ductless system will be completed during Phase II of the project, along with a study of the thermal performance of the demonstration system.

BACKGROUND

Most ductless manufacturers are Japanese-owned companies. Ductless systems are used in over three-fourths of all new homes in Japan.[1] Only within the last five years have the systems been largely introduced in the United States. Ductless equipment has found ready acceptance in the U.S. commercial sector where the equipment is more compatible with the need for individual control of offices. Consequently, ductless systems have shown considerable sales growth in the last few years in the U.S. commercial sector.[2]

A split system air conditioner or heat pump is comprised of an outdoor unit and an indoor unit. The outdoor unit houses the compressor and an outdoor coil. The indoor unit contains an air blower and an indoor conditioning coil. A conventional ducted forced-air system typically has a single indoor unit and a single outdoor unit. A ductless system uses an individual indoor unit in each room or zone. The individual units are usually much smaller than a ducted system unit. Thus, ductless systems are often called "mini-splits." Depending on the house layout, a ductless system may require multiple outdoor units, which increases costs.

SYSTEM DESIGN AND INSTALLATION

Except for the distribution system, a ductless heat pump operates in the same manner as a conventional heat pump. The conventional system conditions the air by passing it over a refrigerant coil and then distributing it through a duct system. The ductless system, however, eliminates the ducts by running small-diameter insulated refrigerant lines directly to individual zones or rooms where air is passed over the coils at the indoor unit.

Ductless systems are relatively easy to install. Typically, it takes a team of two installers one day to install a system with up to three zones. Wiring ductless units for both power and controls is easier than wiring a conventional unit since ductless systems do not need remote thermostats.

DISTRIBUTION LOSSES

Distribution losses associated with ductless systems are typically estimated to be 1 to 5 percent. Conversely, the ducts used with forced-air distribution systems have been identified as an important contributor to energy losses in residential buildings in terms of both air leakage and conduction. Air leakage results when ducts are not sealed tightly enough such and conditioned air flows out through joints. Conduction, which is heat loss directly through the walls of the ducts, can account for a large share of energy loss, even in carefully taped and insulated ducts.[3] In a 1980 report,[4] Orlando et. al., studied six homes, five of which were built over basements. Results demonstrated that duct leakage and conductive losses to unconditioned space can increase energy consumption by as much as 25 percent. Modera[5] reviewed several studies to estimate the impact of duct system leakage and suggested that air infiltration rates typically double during blower operation and that average annual air infiltration rates increase by 30 to 70 percent in houses with distribution systems passing through unconditioned spaces. Further evidence of duct leakage was presented for five slab-on-grade homes in Florida[6] and for twenty crawl space homes.[7]

Robison and Lambert[8] developed a statistical comparison of residential air leakage and heating energy use in 500 electric homes, one-half of which were built to 1980 construction practices and one-half of which were built in accordance with the Northwest Model Conservation Standard. The authors found that ducted control homes were 26 percent more leaky than unducted (electric baseboard or radiant heated) control homes and used 40 percent more heating energy.

These studies suggest a potential for significant energy savings by reducing or eliminating duct leakage and conductive losses, at least in the Pacific Northwest and South Atlantic regions. Less is known about the effectiveness of forced-air distribution systems in homes located in the Northeast and North Central regions where basement construction is the typical substructure.

ZONING

Zoned systems respond to the energy demand within a room or zone rather than supplying conditioned air to the entire structure. Although zoning has been used in commercial buildings for sometime, multizone equipment for homes has only recently entered the market.

The advantages of zonal control in homes are several. For example, heating and cooling design capacities can be reduced when each zone has its own thermostat that can respond to changes in solar and/or internal loads. Other benefits include more effective conditioning in homes that have multiple floor levels. Zoning can better respond to stratification and different heating and cooling loads between levels. Thermostat settings in each room or zone can be easily set back in the heating mode and set up in the cooling mode according to the use of each zone. Equipment can also be turned on/off conveniently depending on the use of the zone.

Initial installation costs may also be reduced through zoning. Zoned equipment can be sized to respond to the diversity in heating and cooling loads in the various zones and the interaction between the zones and the building envelope. This diversity may reduce design equipment capacities and lead to the installation of smaller equipment at a lower cost.

The use of zoning combined with a reduction in duct losses offers opportunities for considerable energy conservation. In a report to the California Energy Commission,[9] the Daikin U.S. Corporation stated that the use of a ductless system could potentially reduce annual energy consumption by 30 to 50 percent, with the 30 percent estimate admittedly very conservative. Daikin calculated an annual energy savings in the 40 percent range for the Sacramento area when comparing its multizone ductless system to a single-zone heat pump. Using these relationships on a national basis, the use of zoning could save 1.51 quads of energy per year.

TASKS

The following tasks were conducted by the NAHB Research Center (Research Center) to achieve the project objectives:

Task 1. Review the ductless systems available in the United States and solicit manufacturers' perceptions and concerns regarding the feasibility of ductless systems for new home construction.

Task 2. Review regulatory and code issues regarding ductless systems.

Task 3. Evaluate relative first and life-cycle costs of ducted and ductless heating and air-conditioning systems.

Task 4. Prepare a research plan to evaluate the comfort provided by a ductless system and compare the system's performance to a ducted system.

RESULTS

Results from the above tasks are presented in the following sections.

TASK 1: REVIEW OF PRODUCTS AND MANUFACTURER PERCEPTIONS

A review of the currently available ductless equipment was conducted to identify systems that could be used in homes. In addition, manufacturers were questioned on potential barriers to the use of ductless systems in new construction.

Currently Available Products

Table 1 lists manufacturers of ductless equipment and provides information on their products. The units are available from HVAC distributors that also carry conventional equipment. Both the outdoor and indoor units of ductless systems are available in many sizes and dozens of configurations.

Most indoor units are either mounted directly to the wall or rest on the floor and are therefore highly visible. The wall units average 30 to 40 inches in length, about 10 to 15 inches in height, and 5 to 10 inches in width. Although manufacturers have succeeded in improving the unit's appearance, home owners are likely to find ductless units aesthetically unappealing, at least until the units can be completely recessed into the wall or even into a closet. At present, many systems are outfitted with expensive plastic extrusions and trim that, while meeting certain discriminating requirements for office space applications (Figure 2), give the units an institutional appearance.

Most units also include specially engineered fans, motors, and compressors that satisfy noise requirements. By contrast, conventional units' placement in unoccupied spaces have fewer restrictive noise requirements. Further, given that each inside unit includes a small blower, it requires its own refrigerant lines, electrical lines, and condensate drain as opposed to just one each for a conventional forced-air system.

Nearly all of the units have been designed to serve offices and other areas that have considerably higher demand loads than individual rooms in most homes. As such, many systems have the capacity to serve an entire home. Even some single-zone systems could serve a small entry-level home were they not designed for a single-room application. In some cases, a single-zone system would provide three to four times the capacity required for a single room. By developing a method of supplying multiple rooms with one unit, manufacturers could reduce the number of units required per home and thus bring down overall system costs. The number of indoor units needed is directly related to the house layout, e.g., more "open" layout would require fewer units.

Perhaps the most desirable feature of ductless equipment is its potential to serve more than one indoor unit from the same outdoor unit. To date, three manufacturers offer this feature. Sanyo Fisher, USA, offers a dual-zone system with a 19,200 Btu/hr total heating capacity and a 16,800 Btu/hr total cooling capacity. EMI offers two-, three-, and four-zone systems in a variety of

Table 1
DUCTLESS SPLIT SYSTEM HEAT PUMP EQUIPMENT

Manufacturer	Outdoor Model	Indoor Model	Cooling Capacity (Btuh)	SEER	Heating Capacity (Btuh)	HSPF
Burnham	B121 HC	B121WHP	11,200	10.0	12,500	6.25
	B121HC	B121WHP	12,000	10.1	12,900	7.4
Carrier (Enviroflex)	38QR018C30	40QKE02430	18,000	10.0	17,600	6.8
	38QK00930	42QK00930	10,200	11.0	9,600	7.3
	38QK01230	42QK00930	12,000	10.2	11,500	7.0
	38QR024C30	40QYE02430	24,000	11.0	22,600	7.3
	38QR036C30	40QKE04830	33,000	10.5	33,000	6.8
Friedrich	MR12Y3B	MW12Y3B	11,400	10.1	12,900	7.4
	MR12Y3	MW12Y3	11,400	10.1	12,900	7.4
	MR18Y3B	MW18Y3B	17,500	10.0	19,000	7.3
	MR38Y2	MS38Y2	38,000	9.1	44,000	7.2
Hitachi	RAC-124JHU	RAS-124JHXU	11,400	10.1	12,900	7.4
	RAC-3128JHV	RAS-3128JH	11,400	10.1	12,900	7.4
	RAC-3189JH	RAS-3189JH	17,500	10.0	19,000	7.3
Mitsubishi Electronics	PUH-30G6	PKH-30AK	30,000	10.0	31,200	7.0
	PUHX-36G6	PJHX-36AK1	36,000	10.4	36,400	7.3
	MUH-09EW	MSH-09DW	8,800	10.0	10,300	6.8
	MUH-12EN	MSH-12EN	12,000	10.0	12,000	6.8
	MUH-15EN	MSH-15EN	14,500	10.0	14,000	6.8
	MUHM-18DN	(2)MSH-09DW[2]	17,200	8.9	18,800	6.6
Mitsubishi Heavy	FDC 140HA1	FDK 140HA1	14,000	10.5	14,500	7.4
	FDC 140HA1	FDK 140HA1	14,000	10.5	14,500	7.4
	FDC 260HA1	FDE 260HA1	26,200	10.1	27,800	7.25

Table 1 (continued)

Manufacturer	Outdoor Model	Indoor Model	Cooling Capacity (Btuh)	SEER	Heating Capacity (Btuh)	HSPF
Sanyo Fisher	CH0921	KHS0921	9,000	10.0	10,800	6.8
	CH0922	KHS0922	9,000	10.0	10,900	6.8
	CH1222	KHS1222	11,400	10.0	13,000	6.8
	CH1222	FH1222	11,400	10.0	13,000	6.8
	CH1822	FH1822	16,500	10.0	13,000	6.8
	CH1822	KMH0922X2[2]	16,800	10.0	19,000	7.0
Toshiba	RAS-10BAHV2B[1]	RAS-10BKHV2B[2]	9,900	12.0	12,500	8.1
	RAS-12BAH2B	RAS-12BKH2B	11,600	10.0	13,300	7.3
	RAV-180AH2U	RAV-180KH2U	18,000	10.0	20,000	6.8
	RAV-240AH2U	RAV-240KH2U	24,000	10.0	25,000	7.1
	RAV-240AH2U	RAV-240CH2U	24,000	10.0	25,000	7.1
Typhoon	HP12CU	CHP12CL	12,100	10.0	11,700	6.25
	HP12CU	SHP12LW	12,100	10.0	11,700	6.25
	HP18CU	SHP18CL	15,200	7.8	15,400	5.75
	HP18CU	SHP18LW	15,200	7.8	15,400	5.75
	HP24CU	SHP24CL	23,000	9.0	23,400	6.25
	HP24CU	SHP24LW	23,000	9.0	23,400	6.25
EMI Heat Pump Units (compressor)	MH2-9900[2]		18,600	10.9	17,600	NR
	MH2-2200[2]		22,200	10.0	21,000	NR
	MH2-9200[2]		20,400	10.0	19,500	NR
	MH4-0808[2]		34,600	10.9	32,800	NR
	MH4-0404[2]		42,800	10.0	40,400	NR
	MH4-0804[2]		38,700	10.4	36,600	NR

Table 1 (continued)

Manufacturer	Outdoor Model	Indoor Model	Cooling Capacity (Btuh)	SEER	Heating Capacity (Btuh)	HSPF
EMI Heat Pump Units (compressor)	MH4-9990[3]		27,900	10.0	26,400	NR
	MH4-2220[3]		33,300	10.0	31,500	NR
	MH4-9908[3]		35,900	10.0	34,000	NR
	MH4-2208[3]		39,500	10.0	37,400	NR
	MH4-2204[3]		43,600	10.0	41,200	NR
	MH4-9999[4]		37,200	10.0	35,200	NR
	MH4-2222[4]		44,400	10.0	42,000	NR
	MH4-9922[4]		40,800	10.0	38,600	NR
EMI Air Handlers (wall units)	WHX-09		9,300	N/A	8,800	NR
	WHX-12		11,100	N/A	10,500	NR
	WHX-18		17,300	N/A	16,400	NR
	WHX-24		21,400	N/A	20,200	NR
General Electric Zoneline Heat Pumps	AZ31H06D	These units are through the wall heat pumps. They are not split systems.	6,100	10.0	5,500	NR
	AZ31H09D		8,900	9.5	8,400	NR
	AZ31H12D		12,000	9.0	11,700	NR
	AZ31H15D		14,100	8.8	13,100	NR
	AZ51H06D		6,100	10.0	5,700	NR
	AZ51H09D		9,000	10.8	8,600	NR
	AZ51H12D		12,300	9.8	11,700	NR
	AZ51H15D		14,500	9.3	14,200	NR

[1]Variable-speed compressor   [3]Three-zone capability   SEER and HSPF are efficiency ratings and performance factors.
[2]Two-zone capability   [4]Four-zone capability   NA - Not Applicable   NR - No Rating

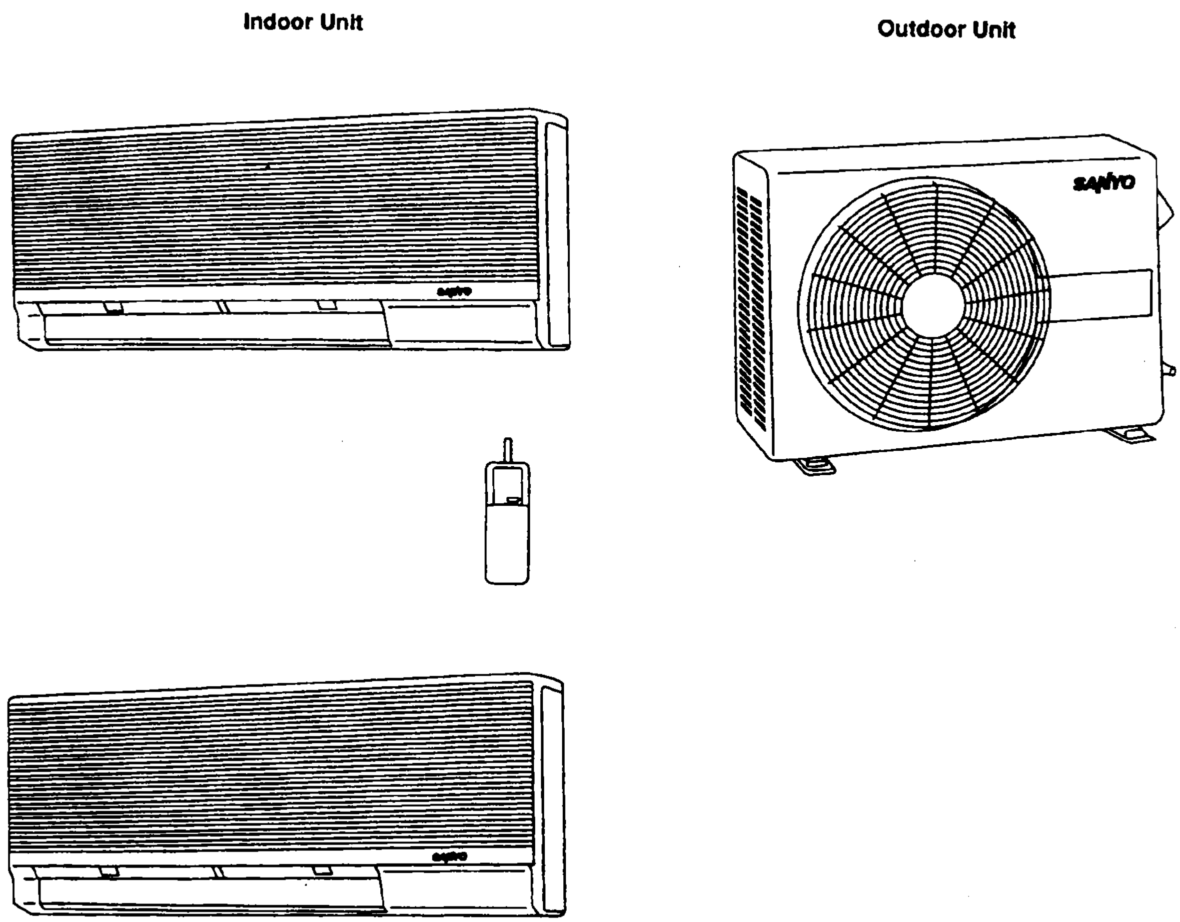

Figure 2. Two-Zone Ductless System
Courtesy of Sanyo Fisher Corporation

capacities. Mitsubishi Electronics also offers a two-zone system with a 17,200 Btu/hr total cooling capacity and an 18,800 Btu/hr total heating capacity.

In summary, the potential energy savings realized by reducing distribution losses associated with ducts and zoning represent considerable benefits. Manufacturers may need to "value engineer" their products to lower costs and make their systems more cost-effective for residential use. They must also work to design a product that home owners will find acceptable.

Manufacturer Perceptions

Research Center staff contacted manufacturers to obtain their perceptions on the use of ductless equipment in homes. The manufacturers' comments generally addressed three areas: costs, potential design modifications, and perceived barriers to the use of ductless technology in homes.

1. Costs

   A. Equipment cost is high due to low demand and special use mentality.

   B. Most systems as currently designed do not cater to multiple-zone residential applications, even though the cost- and energy-savings potential of zoning is evident. Due to the high cost of whole house applications, most manufacturers recommend ductless systems only for additions and retrofits.

   C. Downsizing units for residential use will not likely decrease cost. For example, the cost of manufacturing a 4,000 Btu/h indoor unit is the same as that of a 7,000 Btu/h unit.

   D. Most companies believe that increased demand will decrease cost, although one company's analysis of foreign markets indicated that the cost of the equipment will not decline with increasing demand.

   E. Most manufacturers believe that ductless units are cost-comparative over the long term with other systems, though not on a first cost basis. In terms of first cost, ductless units require digital controls that are more complex than the controls required for a single zone system. Further, the need for fans and motors engineered to reduce noise in the living environment translates into expensive components.

   F. The industry perceives that the only market worth pursuing is the commercial office sector.

2. Design Modifications

   A. Indoor units are sized for commercial use (8,000 Btu/h +) and would need to be decreased in capacity for single room use in residential applications.

   B. Variable-speed compressors need to be developed if multiple indoor units are to be used on a single circuit. (A single, variable-speed compressor unit has recently appeared on the market but is not yet widely available.)

3. Perceived Barriers

   A. The U.S. consumer prefers whole-house central heating and air-conditioning systems as opposed to conditioning part of the house in response to time-use patterns.

   B. Service personnel and parts availability are barriers in the United States.

TASK 2: REVIEW OF REGULATORY AND CODE ISSUES

Research Center staff identified few, if any, code or regulatory barriers that would limit ductless technology. Significant legislation and major energy codes are reviewed below.

Legislation

A review of the energy-related literature reveals a particular regulatory issue dealing with the acceptability of split systems. The U.S. National Appliance Energy Conservation Act (NAECA), which took effect on January 1, 1992, requires split systems to meet a minimum Seasonal Energy Efficiency Rating (SEER) of 10.0 and a Heating Seasonal Performance Factor (HSPF) of 6.8. The ratings are analogous to equipment efficiency and fail to recognize ductless systems' distribution effectiveness. If a total system efficiency was evaluated, incorporating distribution losses, the ductless system with a SEER of 10.0 would have a higher efficiency than a ducted system with a SEER of 10.0.

Third-party testing organizations such as the Air-Conditioning and Refrigeration Institute (ARI) provide lists of unitary air conditioners and heat pumps. ARI is a voluntary, nonprofit organization comprising manufacturers that produce more than 90 percent of the air-conditioning and refrigeration machinery in the United States. Many ductless systems are listed in the ARI Unitary Directory.[10] As shown in Table 1, approximately 15 percent of the ductless systems do not comply with the NAECA requirements.

Energy Codes

Council of American Building Officials (CABO) Model Energy Code.[11] The 1992 CABO Model Energy Code (MEC) does not appear to contain any provisions that limit the use of ductless systems. While the code's equipment efficiency requirements follow the NAECA requirements, most of the code focuses on regulation of the building envelope. The MEC's design requirements are prescriptive; therefore, alternative designs must be proven to meet or exceed those of a comparable prescriptive design. One important requirement relates to the method of handling condensate from the cooling coils. The installation of condensate lines for ductless systems whose units are located on interior walls will require the placement of longer piping in the walls. Drains from units located on exterior walls may pose less of a problem, although aesthetics may be an issue.

American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 90.2 (Pending). Given that Standard 90.2P has yet to be approved, many building codes rely on its precursor, ASHRAE 90A-1980.[12] Nonetheless, the current draft of Standard 90.2P offers two methods for compliance. The first is a prescriptive (i.e., conventional energy-wise construction and equipment efficiency requirements) method; the second is an annual energy cost analysis and a comparison to the specified prescriptive design. If a system is not included in the prescriptive design section, then it must undergo a costly and time-consuming analysis to demonstrate its energy use for each application. ASHRAE 90.2P, Section 6, presents requirements for HVAC systems and equipment. The scope of this section is limited to heat pumps with a rated cooling capacity less than 65,000 Btuh, or approximately 5½ tons. Furthermore, split systems are recognized in all potential combinations of HVAC equipment, including air and ground source heat pumps and air-conditioning units.

ASHRAE 90.2P, Section 3, defines a unitary heat pump as "one or more factory-made units which normally include an indoor conditioning coil, compressor(s) and outdoor coil or refrigerant-to-water heat exchanger, including means to provide both heating and cooling functions. When such equipment is provided in more than one assembly, the separate assemblies shall be designed to be used together." If this definition were interpreted narrowly, the singular use of "indoor conditioning coil" might restrict the number of zones conditioned by ductless systems to one. However, given that the definition starts with "normally include," mini-split ductless system heat pumps with a single outdoor coil and multiple indoor fan coil fall under ASHRAE Section 3 because their separate assemblies are designed to work together.

Section 6.4.2 of 90.2P, Heating and Cooling Equipment Capacity, describes the requirements for sizing multizone cooling equipment, including mini-split ductless systems and ducted systems. In addition, Section 6.5 of the standard, Controls, requires each system or zone to have a thermostat to regulate temperature. The mini-split system would qualify under these requirements.

Given that organizations such as ARI categorize ductless systems as unitary units, and test them to the same specifications as conventional heat pumps, no significant barrier seems to exist with respect to ASHRAE 90.2P.

The CEC Standard[13] is included in the evaluation because it is often a good representation of current trends in energy regulations. In conformance with the CEC Building Energy Efficiency Standards, innovative HVAC systems must be subjected to an approval process similar to that prescribed by ASHRAE 90.2P, except that a public domain computer program compares the energy use of the proposed nonprescriptive design to a prescriptive design. No problem is foreseen with ductless systems, especially since California has been one of the larger markets for ductless applications.

TASK 3: COST EVALUATION

This section contains a discussion of the equipment costs and installed costs of currently available ductless and ducted equipment. A life-cycle analysis of costs in six cities is also presented for a sample 1200 square foot home.

Equipment Costs

Estimated equipment costs to the installer were obtained from distributors and manufacturers. For single-zone equipment, the range of costs is between $1,083 and $2,263 with an average of $1,600, for equipment 8,000 to 18,000 Btuh in cooling capacity. Costs for the two-zone systems average about $2,100 and the three-zone system costs $3,171.

By comparison, costs for an 18,000 Btuh conventional heat pump were estimated at $1,800. Costs for additional equipment, including ducts, registers, grills, and thermostats for a standard distribution system, were obtained from Means Residential Cost Data[14] and estimated at $800, bringing the total equipment cost to the installer to $2,600. Table 2 presents the costs to the installer of some units that incorporate two or more zones; these units are more compatible with whole-house heating and air conditioning.

Table 2
DUCTLESS SPLIT SYSTEM HEAT PUMPS/COST TO INSTALLER
(two or more zones)

Manufacturer	Model Number	Number of Zones	Heating Capacity Btu/hr	Cooling Capacity Btu/hr	Estimated Cost to Installer
EMI	MH2-9900 with 2 WHX-09 air handlers	2	8,800 x 2	9,300 x 2	$2,068
EMI	MH4-9990 with 3 WHX-09 air handlers	3	8,800 x 3	9,300 x 2	$3,121
Sanyo Fisher	18KMH12	2	19,200	16,800	$2,149

Installed Costs

The installation costs of ductless systems were obtained from four distributors and two manufacturers. Estimates were nearly identical and indicated that a two- or three-zone ductless system can be installed in one day by a two-person team. Using this time allotment and a labor cost estimate of $15.50 per hour from Means, an installation cost of approximately $250 for a multiple-zone ductless system was estimated.

The labor costs for a ducted system were also obtained from Means, which showed that approximately 58 hours are required for installation of a complete ducted system for a 1,200 square-foot home. Using $15.50 per hour, the estimated labor cost was approximately $900, which is broken down into the installation of the heat pump ($200) and the ducts ($700). These results were marked up for builder and installer overhead and profit and used as an input to the life-cycle analysis discussed below.

Life-Cycle Analysis

The life-cycle analysis of ducted and ductless systems follows the method set out in ASTM Standard E917-89.[15] Using the discount formulas known as *modified uniform present value* and *single present value*, the life-cycle costs of installed ducted and ductless system were calculated over the expected service life of the main components.

The ductless systems in Table 2 and a comparable ducted system were assumed to be installed in a new single-family house with approximately 1,200 square feet of living space. Figure 3 shows the home's layout. Equipment costs are commonly part of the final sales price of the home and, as such, are reflected in the mortgage principal if the house is financed.

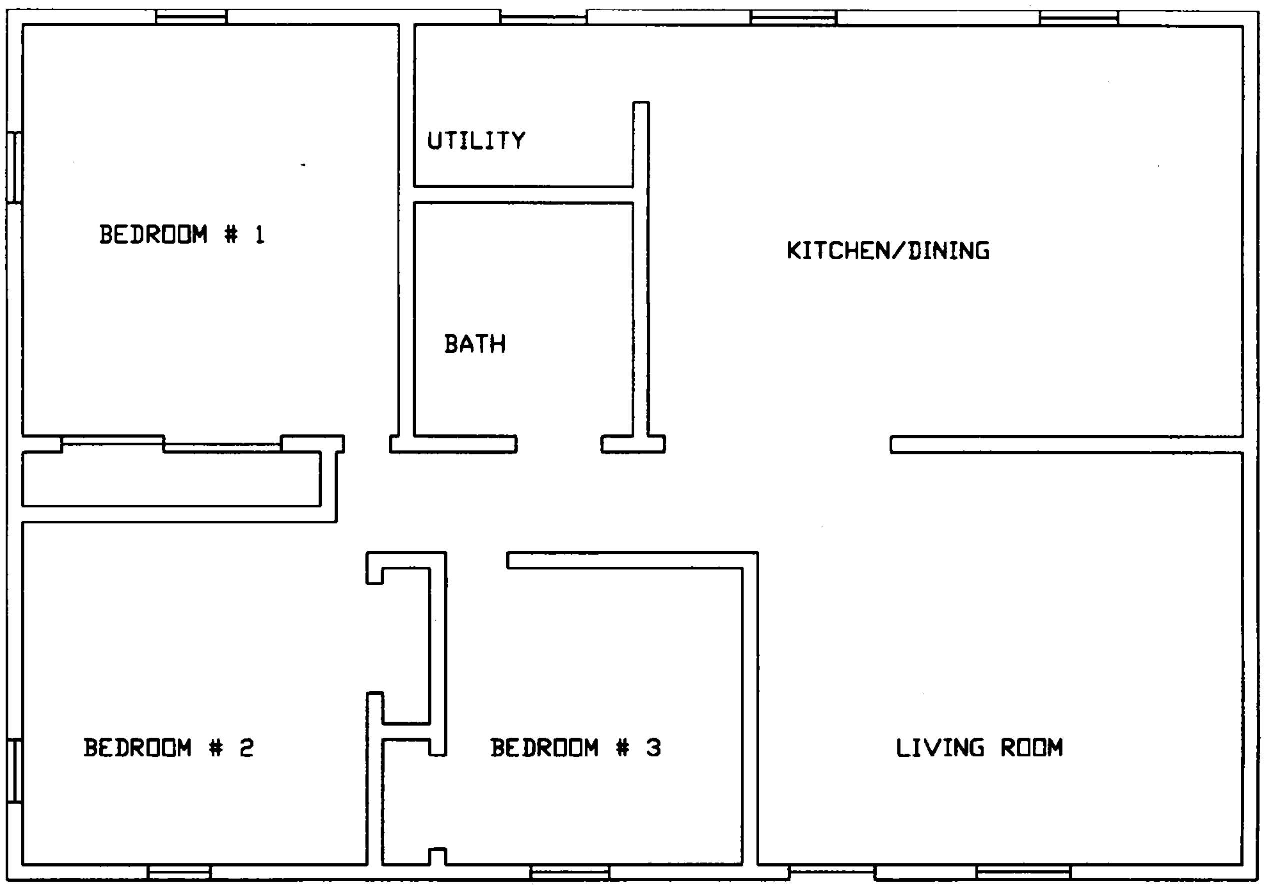

Figure 3. Life-Cycle Cost Example House

Life-cycle costs to year 15 were calculated annually for the end of a given year, 1 through 15, and equal

$$B_t \left(\frac{1}{1+d}\right) + \sum_{t=1}^{n} I_t \left(\frac{1}{1+d}\right) + \sum_{t=1}^{n} O_t \left(\frac{1+i}{1+d}\right) + \sum_{t=1}^{n} M_t \left(\frac{1+i}{1+d}\right) - 0.25\sum_{t=1}^{n} I_t \left(\frac{1}{1+d}\right) - R - V ,$$

where

B_t is the balance of the HVAC portion of the mortgage at the end of year t;
I_t is the interest paid on the HVAC portion of the mortgage in year t;
O_t is the cost of operation in year t;
M_t is the cost of a maintenance contract in year t;
R is the resale value of the outdoor and indoor units at the end of year t;
V is the in-situ value of the ducts or tube set at the end of year t;
i is the annual rate of inflation; and
d is the annualized discount rate.

Assumptions used in this analysis are presented below and the inputs shown in Table 3.

Table 3
INPUTS FOR LIFE-CYCLE COST EVALUATION
Cost to the Home Owner)

	Standard Ducted Heat Pump	EMI MH4 9900	EMI MH4 9990	Sanyo Fisher 18KMH12
Outside Unit	$1,800	$1,047	$1,589	$2,149
Ductless Handlers	*	$1,021	$1,532	Inc
Installation	$200	$250	$250	$250
GC and Installer Mark-Up	$1,200	$1,391	$2,022	$1,439
Subtotal	$3,200	$3,709	$5,393	$3,838
Ducts/Tubes	$800	$360	$360	$360
Installation	$700			
GC and Installer Mark-Up	$900	$216	$216	$216
Subtotal	$2400	$576	$576	$576
Cost to Home owner	$5600	$4,285	$5,969	$4,414
Amount Financed	$5040	$3,856	$5,372	$3,973
Down Payment	$560	$429	$597	$441
Expected Heat Pump/Splits Life	15 years	15 years	15 years	15 years
Expected Tube Life	NA	20 years	20 years	20 years
Expected Duct Life	30 years	NA	NA	NA
Resale Value at End of Life	$0	$0	$0	$0
Discount Rate	10%	10%	10%	10%
Inflation Rate	5%	5%	5%	5%

* Cost of air handler included in outside unit.

- *Initial Equipment Costs*

  For the ductless system, costs to the builder were obtained by applying a mark-up to the costs presented in Table 2. The cost to the builder of the tubing was based on 200 feet of tubing, as obtained from distributors and manufacturers' representatives.

  Equipment costs for the ducted heat pump were estimated to be $2,600 as discussed previously. This was also marked up to obtain a cost to the builder.

  The costs for both ducted and ductless systems are estimates. Depending on the manufacturer and the units selected, exact costs will vary. However, the estimates are typical and allow a reasonable comparison between the two types of systems.

- *Installation Labor Costs (see previous section)*

- *Operating Costs*

  To explore the cost impact of using a ductless system in small residential housing, the U.S. Department of Energy's Program for Energy Analysis of Residences (PEAR)[16] was used to evaluate annual operating costs for both ductless and ducted systems installed in houses with different foundation types in different cities. Appendix A provides a complete description of the PEAR analysis.

- *Discount Rates*

  The annual rate of inflation was set at 5 percent; the annualized discount rate was set at 10 percent.

- *Mortgage Financing*

  The equipment was financed at 90 percent of value and amortized over 30 years. The fixed-rate mortgage carried an annual rate of 10 percent.

- *Maintenance Costs*

  Based on 1992 costs, estimated service contract costs of $176 and $200 per year were obtained from Sears, Roebuck, and Company for a new ducted heat pump system in its fourth and tenth years, respectively. These estimates were inflated by 5 percent to bring them to January 1993 price levels. Estimates for the first through fifteenth years were then made by extrapolating the fourth and tenth year costs. No estimate was available for annual service contracts on ductless systems and thus it was assumed to be equivalent to the service contract on a ducted system.

- *Tax Deduction*

  The home owner's deduction rate was assumed to be 25 percent over the study period.

- *Resale and In-situ Values*

  The expected service life of both the ducted and ductless outdoor units and ductless interior units was assumed to be 15 years. Ducts are expected to last 30 years, and tube sets are expected to last 20 years. The values were estimated by using straight-line depreciation over the expected life of the equipment. The values were not discounted over the life-cycle period.

- *General Contractor's Mark-Up*

  A 60 percent general contractor mark up factor was applied to obtain labor and equipment costs to the home owner. The factor was based on conversations with contractors and was supported by Means.[14]

Results of the life-cycle cost analysis are shown in Tables 4 through 9. The tables show the life cycle costs, in present year dollars, for years 1 through 15.

Table 4
ATLANTA LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	EMI MH4 9900 Two-Zone	EMI MH4 9990 Three-Zone	Sanyo-Fisher 18KMH12 Two-Zone
1	$701	$653	$715	$658
2	882	906	880	904
3	1,586	1,556	1,607	1,560
4	2,277	2,196	2,326	2,206
5	2,957	2,824	3,035	2,841
6	3,625	3,442	4,737	3,465
7	4,281	4,049	4,429	4,078
8	4,926	4,625	5,113	4,681
9	5,559	5,231	5,787	5,274
10	6,181	5,806	6,453	5,856
11	6,791	6,371	7,110	6,428
12	7,390	6,926	7,758	6,990
13	7,979	7,471	8,397	7,542
14	8,557	8,007	9,028	8,085
15	9,124	8,533	9,651	8,619

Table 5
HOUSTON LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	EMI MH4 9900 Two-Zone	EMI MH4 9990 Three-Zone	Sanyo-Fisher 18KMH12 Two-Zone
1	$741	$685	$747	$690
2	960	968	943	966
3	1,700	1,648	1,698	1,652
4	2,426	2,315	2,445	2,325
5	3,139	2,970	3,181	2,986
6	3,839	3,613	3,907	3,636
7	4,525	4,244	4,624	4,273
8	5,199	4,863	5,331	4,899
9	5,859	5,471	6,027	5,513
10	6,507	6,067	6,714	6,117
11	7,143	6,652	7,391	6,709
12	7,766	7,226	8,058	7,290
13	8,377	7,789	8,716	7,861
14	8,977	8,342	9,364	8,421
15	9,565	8,885	10,003	8,971

Table 6
PHILADELPHIA LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	EMI MH4 9900 Two-Zone	EMI MH4 9990 Three-Zone	Sanyo-Fisher 18KMH12 Two-Zone
1	$957	$859	$921	$864
2	1,382	1,308	1,283	1,307
3	2,318	2,147	2,198	2,151
4	3,232	2,966	3,095	2,976
5	4,125	3,765	3,976	3,782
6	4,995	4,546	4,841	4,569
7	5,845	5,309	5,689	5,338
8	6,674	6,054	6,522	6,090
9	7,484	6,782	7,338	6,825
10	8,273	7,493	8,140	7,542
11	9,044	8,187	8,926	8,244
12	9,797	8,866	9,698	8,929
13	10,532	9,529	10,455	9,600
14	11,249	10,177	11,198	10,255
15	11,950	10,810	11,928	10,896

Table 7
SAN FRANCISCO LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	EMI MH4 9900 Two-Zone	EMI MH4 9990 Three-Zone	Sanyo-Fisher 18KMH12 Two-Zone
1	$552	$531	$593	$536
2	590	667	641	665
3	1,157	1,206	1,257	1,210
4	1,719	1,739	1,869	1,749
5	2,275	2,266	2,477	2,282
6	2,824	2,787	3,081	2,810
7	3,367	3,301	3,681	3,331
8	3,904	3,809	4,277	3,845
9	4,434	4,311	4,867	4,353
10	4,957	4,805	5,452	4,855
11	5,474	5,294	6,032	5,350
12	5,983	5,775	6,607	5,839
13	6,486	6,250	7,177	6,321
14	6,983	6,719	7,741	6,798
15	7,472	7,181	8,299	7,267

Table 8
TAMPA LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	EMI MH4 9900 Two-Zone	EMI MH4 9990 Three-Zone	Sanyo-Fisher 18KMH12 Two-Zone
1	$726	$673	$735	$678
2	931	944	919	942
3	1,657	1,613	1,663	1,617
4	2,371	2,269	2,399	2,279
5	3,072	2,914	3,125	2,930
6	3,760	3,548	3,842	3,570
7	4,435	4,169	4,549	4,198
8	5,098	4,780	5,247	4,816
9	5,748	5,379	5,935	5,422
10	6,386	5,967	6,614	6,017
11	7,012	6,544	7,283	6,601
12	7,627	7,111	7,943	7,175
13	8,229	7,667	8,594	7,739
14	8,821	8,214	9,235	8,292
15	9,401	8,750	9,868	8,836

Table 9
WASHINGTON, DC LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	EMI MH4 9900 Two-Zone	EMI MH4 9990 Three-Zone	Sanyo-Fisher 18KMH12 Two-Zone
1	$874	$792	$854	$796
2	1,219	1,177	1,151	1,175
3	2,079	1,953	2,004	1,957
4	2,921	2,714	2,843	2,724
5	3,744	3,457	3,668	3,472
6	4,548	4,185	4,479	4,207
7	5,335	4,897	5,277	4,926
8	6,104	5,593	6,060	5,629
9	6,856	6,274	6,830	6,317
10	7,591	6,940	7,587	6,990
11	8,309	7,592	8,331	7,649
12	9,012	8,230	9,062	8,294
13	9,699	8,855	9,781	8,926
14	10,371	9,466	10,488	9,544
15	11,028	10,064	11,182	10,150

Life-cycle costs are highly sensitive to the assumptions incorporated into the analysis. Two elements drive the differences in life-cycle costs between the ducted and ductless systems: energy costs and resale value.

In all cities, annual energy costs for the ducted system were estimated to be about 20 percent higher than for the ductless systems, to account for distribution losses and zoning. Therefore, as utility costs increase, the importance of energy savings in the comparative cost attractiveness of ductless systems also increases. In all cities, the ductless systems appear to be at least competitive with ducted systems on a life-cycle cost basis. For example, life-cycle costs for the ductless systems appear better than ducted systems in Philadelphia, the city with the highest energy consumption of the six cities evaluated by PEAR. In San Francisco where energy consumption is relatively low, the two-zone systems appear competitive to ducted systems, while the three-zone system does not.

Life-cycle costs are also highly sensitive to assumptions about resale and in-situ value. Because ducts are a large proportion of the cost of the ducted system and have substantial in-situ value well beyond the expected life of other system components, the duct in-situ value tends to help offset any energy savings achieved by the ductless systems when the two systems' life-cycle costs are compared.

First Year Consumer Expenditures

Another way of viewing the expenditures associated with HVAC systems and operations is to estimate the amount of money a household spends out-of-pocket each year. In the first year, these expenses are the sum of the down payment on the HVAC unit, the portion of the principal on the mortgage loan, interest on the mortgage balance, the cost of a maintenance agreement, and the cost of energy to run the unit, less an income tax deduction for the portion of interest paid. Table 10 shows the calculation for the four HVAC units and six cities studied.

This approach is commonly called an *expenditure analysis*. It should be employed with caution since it does not reflect the total economic cost to the household but merely reflects money spent by the household.

Table 10
FIRST YEAR OUT-OF-POCKET EXPENDITURES

Source of Expenditures	Standard Ducted Heat Pump	EMI MH4 9900 Two-Zone	EMI MH4 9990 Three-Zone	Sanyo-Fisher 18KMH12 Two-Zone
Down Payment	$560	$429	$597	$441
Principal	28	21	30	22
Interest	503	385	536	396
Maintenance	173	173	173	173
Tax Deduction	(126)	(96)	(134)	(99)
Subtotal	1,138	912	1,202	933
Energy Costs				
Atlanta	429	355	355	355
Houston	471	389	389	389
Philadelphia	697	571	571	571
San Francisco	272	227	227	227
Tampa	455	376	376	376
Washington	609	501	501	501
Total First Year Costs				
Atlanta	1,567	1,267	1,557	1,288
Houston	1,609	1,301	1,591	1,322
Philadelphia	1,835	1,483	1,773	1,504
San Francisco	1,410	1,139	1,429	1,160
Tampa	1,593	1,288	1,578	1,309
Washington	1,747	1,413	1,703	1,434
Unweighted Average	1,627	1,315	1,605	1,337

Summary of Cost Studies

It appears that some ductless heat pumps can be cost-competitive with ducted heat pumps from both a first cost and life-cycle perspective. This is, however, highly dependent on the specific equipment and number of zones within a home. Ductless systems will likely be more competitive in smaller, "open" homes. The three-zone system was evaluated along with the two-zone systems since it would provide better air movement and comfort in the sample homes.

Although the ductless systems used for cost comparisons are of adequate capacity to meet the overall demand of the sample home, it was necessary to assume that they are capable of providing adequate thermal comfort to each room of the home. Further research is necessary to confirm this assumption.

TASK 4: RESEARCH PLAN

To evaluate the performance and installation of a ductless system, a demonstration home will be constructed in Phase II of this project. The house will be instrumented and monitored for energy consumption and human comfort. Along with these quantifiable measurements, general impressions from the occupants will be factored into future recommendations submitted to manufacturers of ductless equipment. Actual installation costs will also be obtained for comparison with the estimated installation costs used in this report.

A builder in the Baltimore, Maryland, area has been selected to construct the demonstration house, which will showcase both innovative designs and the ductless system technology. The house is a two-story duplex with an unconditioned basement and approximately 1,100 square feet of living area.

Two HVAC systems will be installed in the same demonstration home. The first is a conventional heat pump system, identical to systems used in other units in the development in which the demonstration home will be constructed. The second is the ductless system (Figures 4 and 5). Appendix B includes the heating and cooling load calculations, based on the Right J software package. Energy use and comfort will be monitored for comparison of the two systems over one summer and one winter. Appendix C describes a proposed testing program and discusses thermal comfort testing.

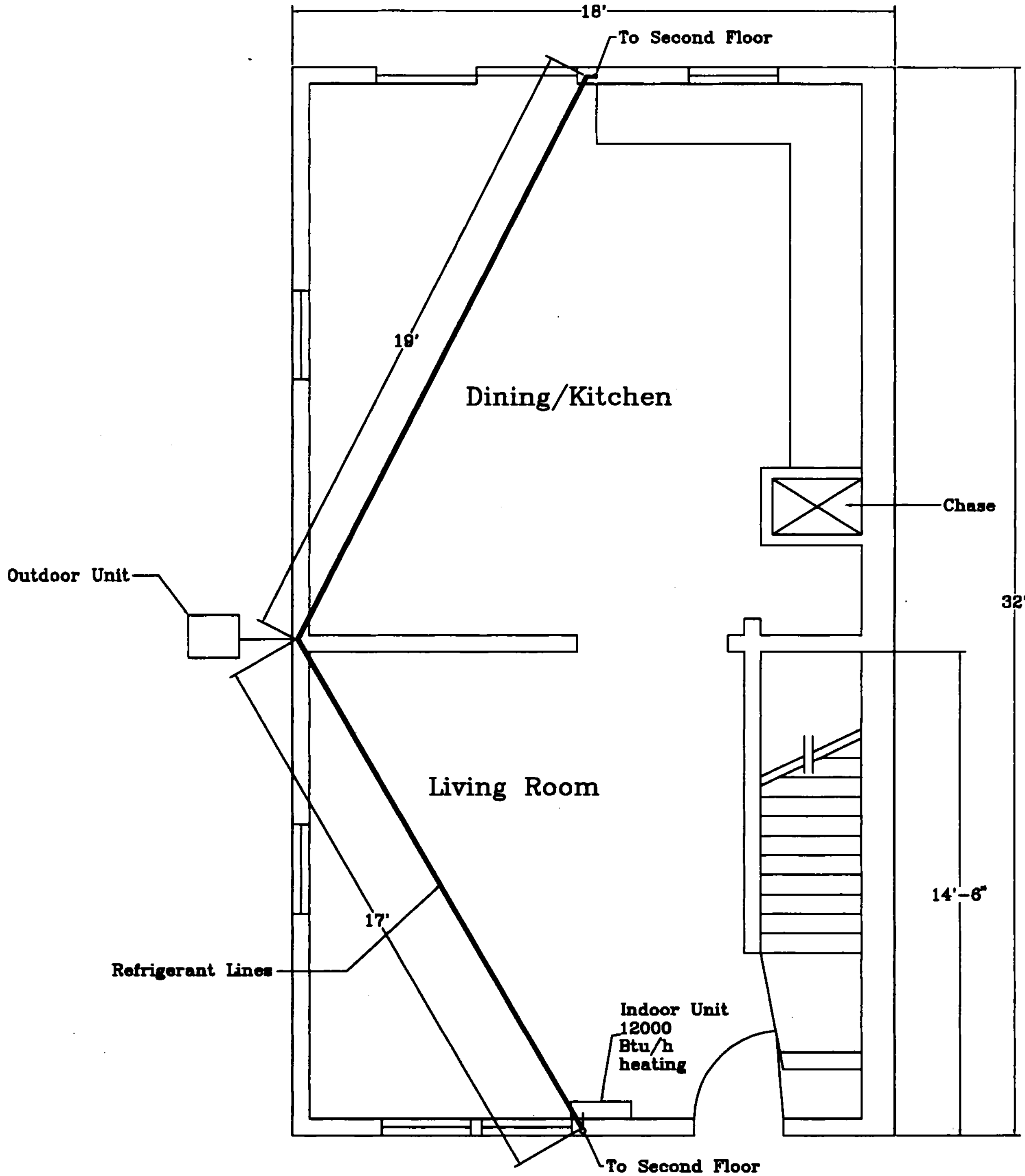

Figure 4. Demonstration Home - First Floor
(Note: Refrigerant lines may be run outside or in basement.)

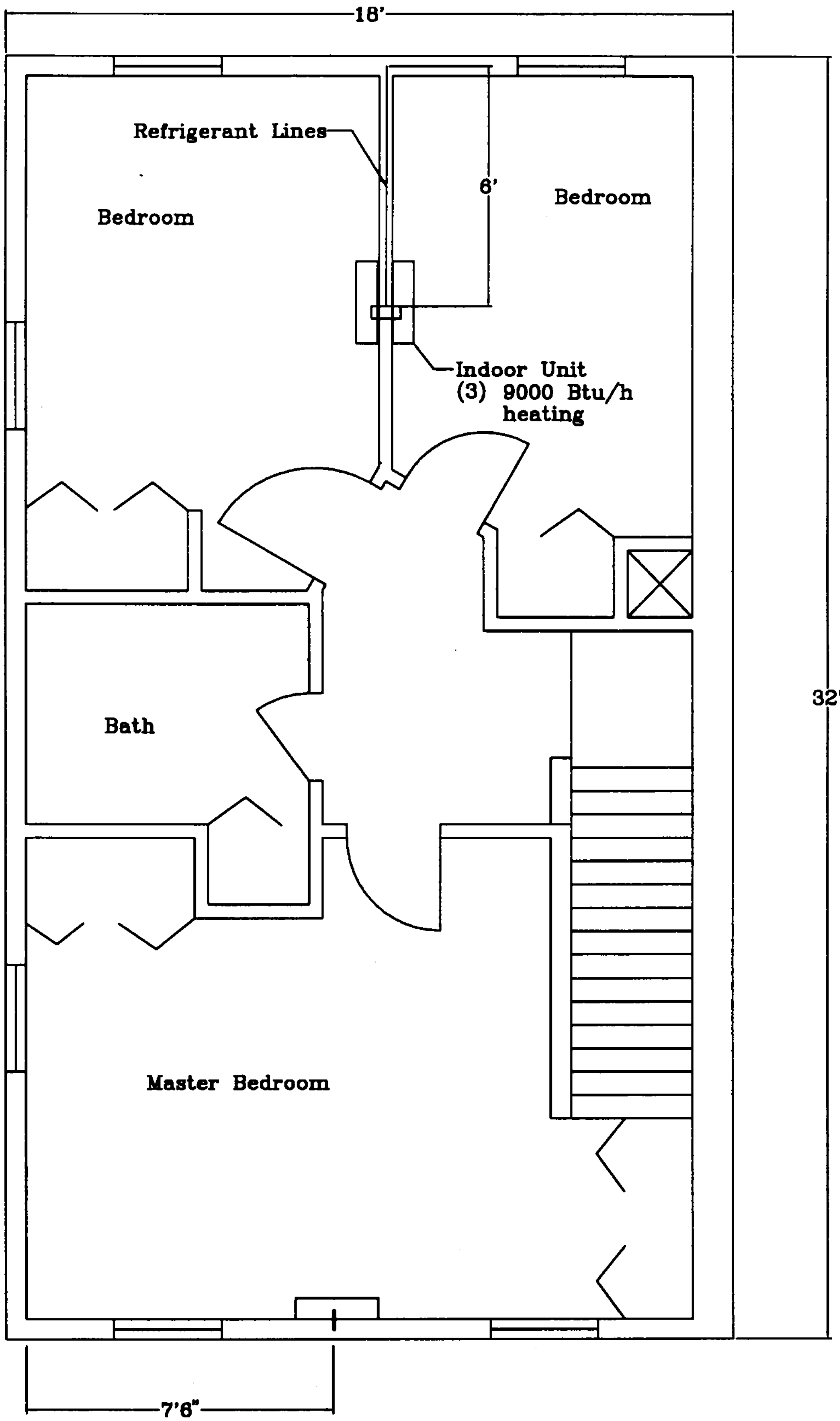

Figure 5. Demonstration Home - Second Floor
(Note: Refrigerant lines may be run outside or in walls.)

RECOMMENDATIONS

Recommendations based on the information collected under this project can be classified into three categories:

DESIGN MODIFICATIONS

Modify ductless units to permit their installation in walls or ceilings and to allow the units to serve two or more rooms with similar time-demand patterns. Currently available indoor units provide much higher-capacity heating/cooling service than that required of many rooms in a typical house. If a single unit could serve more than one room, the number of units could be decreased to create a better match between loads and units. Combining rooms for one unit may also alleviate home owners' potential objections to the aesthetics of ductless systems since the units could then be recessed into the wall or ceiling.

Develop systems that will run multiple indoor units on one compressor. Currently, each indoor unit is matched to its own compressor, i.e., three indoor units require three outdoor compressors. Reducing the number of compressors should decrease the cost of ductless systems.

If a constant-volume compressor is used to serve multiple indoor units, the capacity of each coil will be less than the capacity of any single coil when it is the only coil in operation. When one zone load is met, the coil will turn off and the capacity of the coils in the still unsatisfied zones will increase. The individual indoor coils will respond to partial load conditions by maintaining a constant sensible capacity while increasing the latent capacity. Therefore the sensible heat ratio of the active coils decreases at partial load conditions. This decrease allows the sensible heat ratio of the active coils to match the sensible heat ratio of the building, which helps control humidity in the home.

Multiple coils on one compressor will increase system efficiency as more units become active. According to the NAECA regulations, the SEER of a system might fall below the acceptable minimum if a multi-zone system is evaluated in terms of each individual unit's operation.

Develop the use of variable-flow compressors with multiple indoor coils. The use of variable-flow compressors will correct the efficiency restriction associated with constant-volume compressors and multiple indoor coils. The compressor will supply the exact amount of refrigerant needed to meet the current load within individual zones, thereby keeping the efficiency constant at partial load conditions.

COST REDUCTION MEASURES

Eliminate nonessential components. Many currently available ductless units feature advanced electronic controls that increase the cost of the systems. One manufacturer offers a unit with 22 different functions. By simplifying the electronic controls, the cost of the units will decrease. Many manufacturers contacted in this study expressed reluctance to simplify their controls. They feared that simplification would represent a departure from the state of the art.

Modify the housings used on indoor units. Many ductless units use expensive plastic housings. When units are designed to be recessed into the wall and ceiling, less of the unit will be exposed to aesthetic scrutiny. The expensive housings can then be replaced by less expensive types of plastic or metal.

Examine hybrid systems. A system that combines ductless systems with parts of the ducted system may be the most cost-effective system. For example, it may be possible to install short lengths of ducts from currently operating indoor units to an adjacent room or zone that has a time-demand pattern similar to that of the room that houses the indoor unit.

FUTURE STUDIES

Demonstration of ductless technologies in a home. The demonstration house will provide an opportunity to monitor occupant comfort and energy consumption. Full comfort and energy studies will be conducted to examine the viability of ductless systems in residences.

Work with manufacturers to make ductless systems more compatible with homes. It is important to work with manufacturers to reduce the up-front costs associated with ductless systems. There is also the opportunity to look at foreign markets to learn what makes ductless HVAC systems popular in those markets.

CONCLUSIONS

Ductless systems have the capability to be more energy-efficient than conventional systems. They offer an easy method of zonal distribution in a house. Ductless systems also permit home owners to set their own operating schedules by controlling setup and setback strategies.

From a first cost standpoint, the use of ductless systems in their present form may be justified in some new construction depending on the house layout and number of zones. The cost of ductless systems will, however, decrease as demand increases, and sales will increase if ductless system manufacturers create and market a ductless system that is compatible with home construction. As sales increase, the market will become more viable and the cost of the system should decrease.

By reducing the first costs, ductless systems can become a more viable alternative in new residential housing. To achieve this objective, manufacturers need to change their marketing focus. They also need to implement new designs or even introduce designs used in other countries. Phase II of this project calls for Research Center personnel to work with manufacturers to develop and test lower-cost systems.

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Appendix A
PEAR ANALYSIS

Program for Energy Analysis of Residences (PEAR) was developed as an integral part of Affordable Housing Through Energy Conservation: A Guide to Designing and Constructing Energy-Efficient Homes.* The PEAR guidelines provide a way to evaluate various energy conservation methods based on energy consumption. They also provide a method for comparing the energy and cost savings of different scenarios at one time by using a 45-city data base developed in simulations based on the DOE-2 computer program. Five prototype buildings are included in the program: a one-story dwelling, two-story dwelling, split-level dwelling, middle-unit townhouse, and end-unit townhouse. Other options include combinations of ceiling, wall, and foundation insulation; windows; and infiltration rates. Foundation options include slab-on-grade, crawl space, and heated and unheated basements.

Standard building operation was modeled, including internal loads and occupancy schedules. A schedule was also developed for the summer to use natural venting when feasible to remove excess heat. The program computes a building's energy consumption by simulating the building's hour-by-hour performance for each of the 8,760 hours in a year.

A 1,200-square-foot one-story house was selected for analysis, the foundation varied in accordance with the predominate foundation type in the region of the selected city. PEAR specifies the typical construction for each region. The input for the ceilings is the nominal R-value of the insulation only. The program assumes 2x6 24-inch on center (o.c.) ceiling construction with an attic. The walls are handled in the same way except for a nominal R-value of the insulation with 2x4 16-inch o.c. light weight wall construction. The foundation insulation was selected to minimize differences in foundations and to depict typical construction. For the ventilated crawl space and basement, a floor construction of 2x10 24-inch o.c. was used. The insulation for the ceilings and walls was kept constant regardless of foundation type. The windows in the house are standard 1/8-inch glass with a 1/4-inch air gap for double pane. The sash is aluminum with thermal breaks. The infiltration input is that for the average number of air changes per hour during the winter months. Table A-1 shows the inputs for the house characteristics. The inputs demonstrate typical construction practices and were kept constant for all sites to minimize any discrepancies.

The evaluation used an electric heat pump for both cooling and heating and a gas furnace for heating with an electric condenser for cooling. For the equipment efficiency, the NAECA minimum was selected. PEAR accepts only one value for efficiency; it must be a system efficiency that incorporates duct losses where applicable. The duct losses were assumed to be 10 percent of the energy received. The ductless system was modeled by using the heat pump setting, but the duct loss was not incorporated into the efficiency, and the system was derived 10 percent more efficient due to zoning. The overall difference in delivered efficiency between the two systems was 20 percent. This was true for all cases since the basement was unconditioned.

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*Applied Science Division, Lawrence Berkeley Laboratory, University of California. *Affordable Housing Through Energy Conservation--A Guide to Designing and Constructing Energy Efficient Homes.* U.S. Department of Energy Contract No. DE-ACO3-76SF-00098 (June 1989).

Table A-1

GENERAL INPUT		
State		
City		
Prototype	1S	
Foundation Type	Slab, Basement, Ventilated Crawl Space	
Floor Area	1,200 Square Feet	
Wall Perimeter	138 Feet	
Gross Wall Area	1,328 Square Feet	
North Window Area	35 Square Feet	
South Window Area	35 Square Feet	
East Window Area	20 Square Feet	
West Window Area	10 Square Feet	
CONSERVATION MEASURES		
Ceiling Insulation	30.0 R-Value	
Roof Color	Dark	
Wall Insulation	13.0 R-Value	
Wall Mass Location	None	
Foundation Insulation	R5-2, R10-8, None	
Floor Insulation	0, 0, R-19 R-Value	
Window Layers	2 Pane	
Window Sash Type	Aluminum with Thermal Breaks	
Window Glass Type	Regular	
Window Movable Insulation	None	
Infiltration	0.5AC/hr	
EQUIPMENT		
Heating Equipment	Heat Pump--6.1 HSPF, Ductless--7.5 HSPF Gas Furnace--80 percent	
Efficiency		
Night Setback	No	
Cooling Equipment	HP (ductless)	
Efficiency	9.0 SEER (11.0--zoning)	
APPLIANCES		
Domestic Hot Water		
Type	Electric, Gas	
Yearly Electric Consumption Rating	$235, 130	
Conservation Option	None	
Refrigerator		
Yearly Electric Consumption Rating	$60	
Dishwasher		
Yearly Consumption Rating	$70(electric), $30(gas)	
Loads/Week	5	
Clothes Washer		
Yearly Consumption Rating	$80(electric), $35(gas)	
Loads/Week	4	
Reference Electric Price	0.0779 $/KWh	
Reference Gas Price	0.595 $/th	

Economics	HP	MS	GF
Capital Cost	3,000	5,000	6,500
Lifetime	15	15	15
Escalation Rate		5.0%	
Discount Rate		10.0%	
Interest Rate on Loan		10.0%	
Loan Period		30 years	

PEAR aggregate the heating and cooling costs and displays them as an HVAC cost, which is the annual operating cost of the system. The program's default electric and gas prices were chosen for the evaluation and were kept constant to provide a better comparison between systems' and cities' energy consumption. The author of PEAR recognizes that utility costs vary with location.

The life-cycle cost of operating a building under different economic constraints can strongly influence basic design decisions. The reason is that energy consumption is also affected by the operation of primary and secondary HVAC, and the type and efficiency of the equipment. Table A-2 shows the results of the PEAR analysis of annual energy consumption for six U.S. cities. The cities were selected to offer a broad range of environments in the United States. A duct loss of 10 percent of the energy was assumed, while zoning was assumed to save 10 percent of energy. The thermostat settings for PEAR were 70°F for heating and 78°F for cooling, which were incorporated into the HSPF and SEER of the heat pump units. The gas furnace was included in the analysis for areas where basements are prevalent. The simple payback for both the ductless system and the gas furnace was based on the cost difference between a conventional heat pump system and the comparison system.

Table A-2
ANNUAL ENERGY COSTS (Dollars)

	HP	MS	GF
Atlanta--slab	428.7	355.3	
Washington--basement	609.2	500.5	420.4
Tampa--slab	455	375.9	
San Francisco--slab	272.1	227.2	
Philadelphia--basement	696.6	571.2	455.2
Houston--slab	470.5	388.7	
Simple Payback (Base Case (HP)) (years)			
		MS	GF
Atlanta		68.2	
Washington		46.0	34.4
Tampa		63.2	
San Francisco		111.3	
Philadelphia		39.9	26.9
Houston		61.1	

1. Heat Pump--HP
2. Mini-Split--MS
3. Gas Furnace--GF

Appendix B

S/N 480

RIGHT-J SHORT FORM

12-1-92

Job #: 4406

For: Demonstration House

Baltimore, MD

By:

	Htg	Clg
Outside db	13	91
Inside db	70	75
Design TD	57	16
Daily Range	-	M
Inside Humid.	-	50
Grains Water	-	42

Const. Quality a
\# of Fireplaces 0

HEATING EQUIPMENT		COOLING EQUIPMENT	
Make		Make	
Model		Model	
Type		Type	
Efficiency/HSPF	0.0	COP/EER/SEER	0.0
Heating Input	0 Btuh	Sensible Cooling	0 Btuh
Heating Output	0 Btuh	Latent Cooling	0 Btuh
Heating Temp Rise	0 Deg F	Total Cooling	0 Deg F
Actual Heating Fan	478 CFM	Actual Cooling Fan	478 CFM
Htg Air Flow Factor	0.024 CFM/Btuh	Clg Air Flow Factor	0.048 CFM/Btuh
Space Thermostat		Load Sensible Heat Ratio	83

ROOM NAME	AREA SQ.FT.	HTG BTUH	CLG BTUH	HTG CFM	CLG CFM
Living Room	252	5,005	2,083	121	100
Dining/Kitchen	324	5,788	3,263	140	156
Master Bedroom	216	4,731	2,172	114	104
Bedroom 1	108	2,250	1,517	54	73
Bedroom 2	122	1,698	832	41	40
Bathroom	39	277	123	7	6
Entire House	1,060	19,749	9,989	478	478
Ventilation Air		0	0		
Latent Cooling			2,022		
TOTALS	1,060	19,749	12,012	478	478

S/N 480

RIGHT-J SHORT FORM

07-15-92

Job #: 4406

For: Demonstration House

Baltimore, MD

By:

	Htg	Clg
Outside db	14	90
Inside db	60	85
Design TD	46	5
Daily Range	-	M
Inside Humid.	-	50
Grains Water	-	37

Const. Quality b
# of Fireplaces 0

HEATING EQUIPMENT		COOLING EQUIPMENT	
Make		Make	
Model		Model	
Type		Type	
Efficiency/HSPF	0.0	COP/EER/SEER	0.0
Heating Input	0 Btuh	Sensible Cooling	0 Btuh
Heating Output	0 Btuh	Latent Cooling	0 Btuh
Heating Temp Rise	0 Deg F	Total Cooling	0 Deg F
Actual Heating Fan	375 CFM	Actual Cooling Fan	375 CFM
Htg Air Flow Factor	0.017 CFM/Btuh	Clg Air Flow Factor	0.043 CFM/Btuh
Space Thermostat		Load Sensible Heat Ratio	83

ROOM NAME	AREA SQ.FT.	HTG BTUH	CLG BTUH	HTG CFM	CLG CFM
Living Room	205	7,743	2,180	129	94
Dining/Kitchen	252	5,689	3,093	95	134
Bedroom 1	158	3,888	1,684	65	73
Bedroom 2	98	1,918	460	32	20
Bedroom 3	121	3,235	1,249	54	54
Entire House	834	22,473	8,665	375	375
Ventilation Air		0	0		
Latent Cooling			4,982		
TOTALS	834	22,473	13,647	375	375

Appendix C
THERMAL COMFORT TESTING

The thermal performance of an occupied space is determined by the design and construction of the space as well as by the HVAC system and corresponding controls used to condition the space. Just as poor construction practices or design can lead to uncomfortable conditions within a building, a poorly performing thermostat may allow the temperature in the controlled space to fall below the desired set point, causing a well-designed HVAC system to perform inadequately. Alternatively, good building design and construction combined with a good HVAC control system may be able to reduce energy consumption and HVAC operating costs.

Thermal comfort has been defined by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) as "that condition of mind which expresses satisfaction with the thermal environment." This condition of comfort is dependent on the following environmental and personal factors, which, when combined in varying magnitudes, determine an individual's thermal comfort level acceptance.[C1]

1. **Dry-Bulb Temperature (T_{db}).** Dry-bulb temperature is the simplest practical index of cold and warmth under ordinary room conditions. It is a measure of room temperature on a standard scale without the effect of direct radiation.

2. **Mean Radiant Temperature (T_R).** Mean radiant temperature is the uniform black body surface temperature with which a person (also assumed a black body) exchanges the same heat by radiation as in the actual environment.

3. **Relative Humidity (RH).** Relative humidity is the ratio of the mol fraction of water vapor present in air to the mol fraction of water vapor present in saturated air at the same temperature and barometric temperature.

4. **Room Air Velocity.** Room air velocity is air movement in an occupied zone. At low air movement, it is difficult to distinguish between air movement resulting from free and forced convection and that caused by body movements.

5. **Activity Level (metabolism).** The metabolic rate is the internal body heat created by energy released in the human body per unit of time. Metabolism is what makes comfort a function of the individual. Metabolism is measured in mets where 1 MET = 18.4 $Btu/hr*ft^2$.

6. **Clothing Level (CLO).** Clothing, because of its insulation value, is an important modifier of body heat loss and comfort. Clothings thermal resistance is measured in CLOs where 1 CLO = 0.88 ft^2 hF/Btu. Typical winter indoor clothing levels have a CLO of approximately 1.0 whereas typical summer indoor clothing levels have a CLO of approximately 0.5.

Due to differences in individual metabolism and preferences, it is impossible to create a thermal environment that will satisfy everyone simultaneously. The objective of most thermal comfort research has been to identify conditions that result in thermal comfort for the highest possible percent of a group. Comfort conditions are said to be met when 80 percent of a given population is satisfied with the thermal comfort environment.[1]

The most widely accepted studies on the characterization of thermal comfort have been conducted by Professor P.O. Fanger of Denmark and by Kansas State University (KSU) for ASHRAE. These studies define indices that characterize the thermal comfort zone in terms derived from the aforementioned environmental and personal factors.[C2]

The Institute for Environmental Research at KSU, under ASHRAE contracts, has conducted extensive research into thermal comfort for clothed sedentary subjects. Studies on 1,600 college-age students showed statistical correlations between comfort level, temperature, humidity, sex, and length of exposure. Elderly subjects exposed to the thermal conditions of the KSU-ASHRAE envelope had responses nearly identical to those of college-age subjects. Fanger found no significant difference between the preferred temperature of younger (mean age 23 years) and elderly (mean age 68 years) subjects. Comfort conditions are also independent of the time of day or night. Fanger also found that although each individual was highly consistent in thermal preference from day to day, preferences differed considerably between individuals.

In the Fanger studies, sedentary subjects in Denmark were subjected to a range of stable thermal conditions in which all six personal and environmental parameters were varied during the course of the experiment. Each person was asked to rate his or her comfort level according to a seven-point psychophysical scale. The scale ranged from -3 (cold) to +3 (hot), with 0 representing thermal neutrality. By averaging the comfort levels across the test subjects, a Predicted Mean Vote (PMV) was determined for each set of conditons. In addition, the data were used to predict the percent of the population that would be dissatisfied with the thermal environment. The Predicted Percentage of Dissatisfied (PPD) is a nomogram of the percent of the test subjects voting -3, -2, -1, 0, +1, +2 or +3 under each thermal condition. The PPD will never fall below 5 percent, even when the PMV is 0 because there is no thermal condition under which all subjects are comfortable.[2]

An iterative thermal comfort equation developed by Fanger calculates the PMV and PPD for a range of activity and clothing levels for various combinations of air temperature, mean radiant temperature, relative humidity, and air velocity.

The PMV and PPD indices express warm and cool discomfort for the body as a whole, although thermal dissatisfaction may also be caused by unwanted heating or cooling of one particular part of the body (local discomfort). This can be caused by an abnormally high vertical air temperature difference between the head and ankles, which is created by a warm or cool floor an unacceptably high room air velocity. Guidelines for some of the more important parameters required to maintain local thermal comfort given varying personal factors are as follows[C3]:

1. The room air temperature should remain between 68°F and 74.8°F during winter months and between 73°F and 79°F during summer months.

2. The vertical temperature difference between 4 inches above the floor and 43 inches above the floor (for seated individual) and 67 inches above the floor (for standing individuals) should be less than 5.4°F.

3. Floor temperature should remain between 65°F and 84°F.

4. Mean room air velocity should remain at less than 30 ft/min during winter months and at less than 49 ft/min during summer months.

5. Indoor humidity limits are broad as long as the humidity levels do not affect indoor air quality. Suggested indoor humidity levels are approximately 30 to 70 percent RH during winter months and 25 to 60 percent RH during summer months.[1]

6. Temperature drifts and ramps are steady, noncyclical temperature changes. Drifts refer to passive temperature changes, while ramps refer to actively controlled temperature changes. Slow rates of operating temperature change (about 1°F/hr) during the occupied period are considered acceptable, provided that the temperature during a drift or ramp does not range beyond the comfort zone by more than 1°F for longer than an hour. If the peak variation in operating temperature exceeds 2°F, then the rate of temperature change should not exceed 4°F/hr. If the peak variation is less than 2°F, then there is no restriction on the rate of temperature change.[1]

TECHNICAL APPROACH

An automated data acquisition system (DAS) can be implemented in an occupied home to monitor relevant environmental factors to determine the extent to which a ductless HVAC system versus a conventional forced-air ducted HVAC system is capable of maintaining thermal comfort conditions. Both systems will be in the same house. A second additional study can be performed to make an operating cost comparison between the ductless system and the conventional ducted system.

The basement is to remain unconditioned throughout the test period and as such, only drybulb temperature at heights of 4 inches above floor, 43 inches above floor, and 67 inches above the floor and humidity at 43 inches above the floor will be monitored at the center of room (COR). These measurements can be used to compare heat loss from the ducted system into the basement as well as to determine the unconditioned basement's impact on first-floor heat loss when a ductless system is used.

Drybulb temperature, mean radiant temperature, and humidity will be monitored at strategic locations on the first and second floors. Optimally, each would be measured COR in the living room, dining room, and upstairs bedrooms; however, because the home is to be occupied, optimal sensor probe positioning and operations protocol, such as door positioning, may need to be compromised to allow minimal inconvenience to the occupants. As such, drybulb temperatures at 4 inches, 43 inches, and 67 inches above the floor; humidity at 43 inches above the floor; and mean radiant temperature at 43 inches above the floor will be measured COR in the living room and at the top of the stairs on the second floor.

Air temperatures at each thermostat location will also be monitored to determine the performance characteristics of the thermostats. A 43 inches, COR temperature will be monitored in each of the three bedrooms. Additional measurements are disregarded in the bedrooms due to probable occupant interaction. Air temperature measurements will also be made COR at 4 inches, 43 inches, and 67 inches above the floor in the dining room.

Outdoor temperature and solar radiation will be monitored and used in comparing the results of the ductless and conventional HVAC system performance. On/off status of each heat pump will be monitored to verify overall operating performance.

A fixed mean room-air velocity of 15 ft/min will be assumed in calculating comfort indices. Three reasons underlie the assumed room-air velocity rate. First, hot wire anemometers (used for air velocity measurements) are delicate instruments that would likely be broken if placed in an occupied zone. Second, hot-wire anemometers are uni-directional. Third, it is difficult to distinguish between air movement resulting from free and forced convection and that caused by body movements.

Fixed clothing levels of 1.0 clo (representing typical indoor winter clothing levels) and 1.0 met (seated, relaxed activity) will also be assumed in calculating comfort indices. A clothing level of 0.5 clo will be used for typical indoor summer clothing levels.

Thermostat settings will be held at 72°F set points throughout all winter tests and at 75°F set point throughout all summer tests and should not be adjusted by building occupants. Testing of each system will alternate on a weekly basis. Each sensor will be scanned at one-minute intervals with minimum, maximum, and average values recorded each hour.

Energy consumption for each system can also be monitored to compare operating costs for the ductless and conventional systems. This would be done by monitoring line voltage and current draw for the ductless units and by using a WATT-transducer to monitor energy consumption associated with the conventional system. The ductless system is designed for a zoned configuration whereas the conventional system is a single-zone system. Since zoned systems traditionally do a better job of maintaining a uniform temperature distribution throughout a building and, by so doing, expel more energy, a direct operating cost comparison may not be totally accurate.

MATERIAL LIST

Description	Vendor	Estimated Cost
Thermistor Probes (22)	Campbell Scientific	$1,200
Humidity Sensors (3)	Vaisala	1,600
Pyronameter (1)	Campbell Scientific	215
Pyronameter Mounting Bracket	Campbell Scientific	44
Status Relays (4)	Dayton	40
Power Supply (1)	Campbell Scientific	100
3-Conductor Communication Wire	Alpha	200
4-Conductor Communication Wire	Alpha	200
Miscellaneous Brackets, Cables, Supplies, etc.	Varied	100
Data Logger and Peripherals	Campbell Scientific	3,427
Modem Telephone Line Installation		400
Subtotal		$7,526
Additional Materials for Energy Consumption Monitoring:		
Watt-Hour Transducer (1)	Ohio Semitronics	$ 550
Voltage Transducer (2)	Ohio Semitronics	140
Current Transducer (3)	Ohio Semitronics	210
Load Resistors (3)	Ohio Semitronics	45
100		
Subtotal		$1,045
Total		$8,572

COORDINATION OF DAS INSTALLATION

A minimum of three site visits by a Research Center engineer will be required to complete the DAS installation. The timing for each of these visits is described below.

First site visit. Immediately following electrical rough-in and before insulating house. The DAS infrastructure will be put in place, after the electrician finishes rough-in to ensure that high-voltage wires do not affect DAS wiring (i.e., noise interference on DAS lines and local codes).

Second site visit. After interior painting is completed. Termination and installation of DAS microprocessor and sensors will be completed.

Third site visit. After occupants move in. Sensor probes will be put in place and the DAS system started for monitoring.

The electrician will be responsible for providing a 120 V_{AC} duplex receptacle and a modem telephone line to the DAS. If heat pump energy consumption is to be monitored, the electrician will be responsible for coordinating the heat pump wiring through the Research Center's DAS system. This will be a UL-approved enclosure located alongside the existing breaker panel box. Additional site visits by the Research Center engineer may be required to solve any unexpected DAS problems that may occur during building construction or during the thermal comfort analysis phase. During building occupancy, home owners will be responsible for activating/ deactivating heating systems on a weekly basis as directed by the Research Center engineer and for logging in a site log book provided by the Research Center major living pattern changes, special events, or problems that may compromise the thermal comfort monitoring results.

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