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 II - Final Report

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EXECUTIVE SUMMARY

This report addresses the use of ductless electric heat pumps for heating and air conditioning of new homes. It includes information on the types and intended applications of currently available ductless systems and their initial, operating, and installation costs. Results of a demonstration home used to evaluate and compare the performance of a ductless system and a conventional heat pump system are also provided. Where appropriate, recommendations to manufacturers for improving ductless equipment and lowering initial costs are provided.

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. Further, ductless systems offer the opportunity for zoned applications that could increase energy saving and comfort.

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 indoor units, which increase 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 setback in the heating mode and setup 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.

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 will likely find ductless units aesthetically unappealing, at least until the units can be down-sized or completely recessed into a 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, a system may 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 with a forced-air ducted system. It appears that some currently available ductless heat pumps can be cost-competitive with ducted heat pumps from both first cost and life-cycle perspectives when home floor plans are uncomplicated and open (e.g. requiring less than three zones). However, when more than three zones are required, the line of currently-available products will not be cost competitive with conventional, ducted heat pump systems. They do provide other benefits such as improved comfort and energy conservation, but without competitive economic payback.

Performance Evaluation

Monitoring the performance of a demonstration home equipped with both ductless and ducted heat pump systems allowed a realistic comparison of the two systems. The two-story townhome was conditioned with two dual-zone (four zones total) ductless systems. Analysis of data collected on both systems during the 1993-94 heating season indicates a potential for energy savings and improved comfort by the ductless system. The occupants were also more satisfied with the comfort provided by the ductless system due to its ability to provide individual control of zones in their home.

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 reduced to lower first costs and 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. Use of variable speed compressors will have the added effect of improving system energy efficiency.

- *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 would 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 system that combines ductless systems with parts of the ducted system may be the most cost-effective system. A hybrid system may allow installation of short lengths of duct from a single indoor unit to serve adjacent rooms or zones.

- *Decrease capacity of indoor units.* Capacities of most currently-available ductless units are greater than is required for the typical residential zone. Decreasing indoor unit capacity and size may only have minimal impact on cost, but it would make the units less obtrusive and easier to locate in a home.

- *Further simplify and improve installation.* Flexible, synthetic refrigerant tubing and quick disconnect style fittings should provide greater ease of installation and removal.

Conclusions

Ductless systems have the capability to be more energy efficient and to provide greater thermal comfort than conventional HVAC systems. They offer an easy method of zonal distribution and thermostat setback control in a house. Ductless systems also permit home owners to set their own operating schedules by controlling setup and setback strategies within different house zones - further improving energy efficiency and comfort.

From a first cost standpoint, the use of ductless systems in their present form may be justified in some new homes with simple house layouts of less than three space-conditioning zones. For most new home applications, the currently-available line of ductless HVAC products do not appear cost effective. As market share increases, it is likely competition will increase, with a related decrease in cost. Further increases in demand will occur if ductless system manufacturers create and market a ductless system that is more compatible with home construction and competitive with current HVAC products used in new homes.

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.

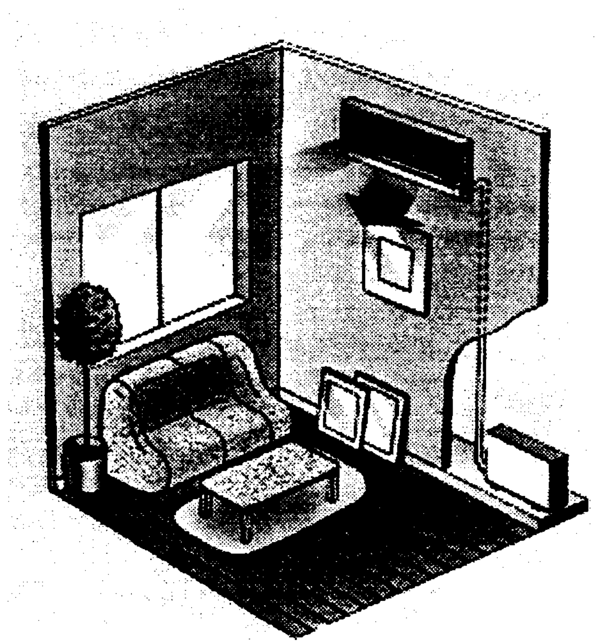


Figure 1. Typical Ductless Heat Pump System
Courtesy of Sanyo Fisher Corporation

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 designed for zoned application, which can further increase energy savings and comfort. Also, most ductless systems are easily programmed for thermostat setback control strategies which create additional energy savings.

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. Identifying the types and intended applications of currently available ductless systems.

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

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

4. Demonstrating a ductless system in a home to gain a practical understanding of its installation requirements.

5. Evaluating and comparing the performance of a ductless system and a conventional heat pump 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 office control. Consequently, ductless systems have shown considerable sales growth in the last few years in the U.S. commercial sector.[2]

SYSTEM DESIGN AND INSTALLATION

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 leads to higher costs.

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. 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 for both power and controls is easier than with a conventional unit since wires are typically run along with the refrigerant lines.

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 tight enough 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 typical.

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 setback in the heating mode and setup 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 multi-zone 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.

SETBACK CONTROL

Setback control strategies allow thermostat set-points to vary according to the time-demand or use pattern for a whole building or individually controlled zone. During the heating season a setback strategy is employed, and a thermostat setup strategy is used during the cooling season. For a typical residential application, a programmable thermostat may be used to setback temperatures by 5 to 10°F during periods of vacancy (e.g. during working hours). For a zoned system, setback strategies may be tuned to the differences in time-demand by zone. Bedrooms may be fully conditioned at night, and setback during the daytime. Energy savings in the range of 10 percent could be expected by use of setback control strategies for a given HVAC system.

TASKS

The following tasks were conducted by the NAHB 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. Evaluate the comfort and energy performance provided by a ductless system in comparison to a conventional ducted system in a demonstration home.

Tasks 1, 2, and 3 were completed in 1993 during Phase I of this project. Consequently, the pricing and availability of some ductless systems may differ slightly from the systems available at the time this report was written. Task 4 was completed in 1994 as Phase II of the project. Also, Task 3 results were revised during Phase II based on experiences derived from the installation and operation of the demonstration home. The results of both phases are presented in this report.

RESULTS

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 will likely 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 in unoccupied spaces have fewer restrictive noise requirements. Further, given that each indoor 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 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.

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

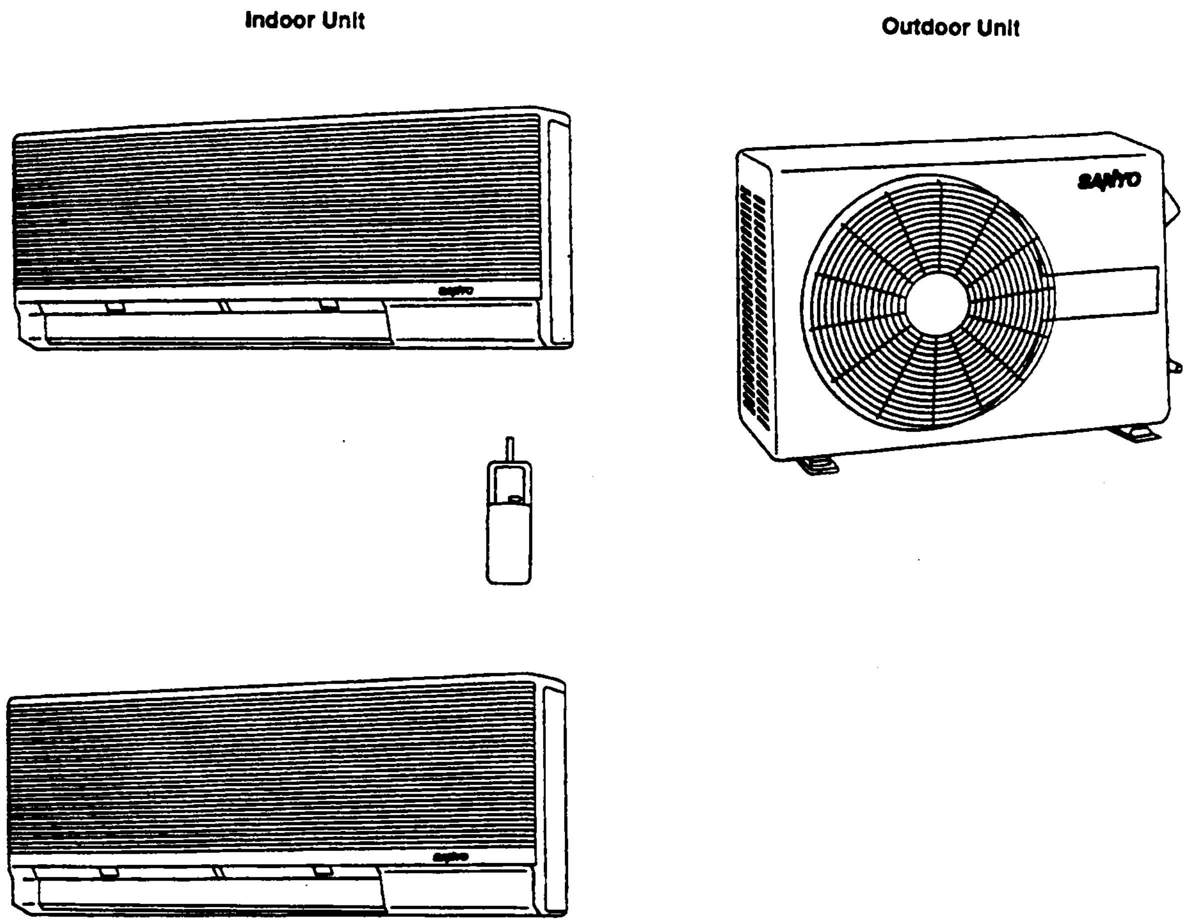


Figure 2. Two-Zone Ductless System
Courtesy of Sanyo Fisher Corporation

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. These comments are summarized as follows:

1. Costs

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

   - 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.

   - 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.

   - 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.

   - 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.

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

2. Design Modifications

   - Indoor units are sized for commercial use (8,000 Btu/h +). Reduced capacities would be needed for single room use in residential applications.

   - 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

   - 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.

   - Service personnel and parts availability are barriers in the U.S.

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 system efficiency than a ducted system with a SEER of 10.0.

Third-party organizations such as the Air-Conditioning and Refrigeration Institute (ARI) provide lists of unitary air conditioners and heat pumps and expected efficiency. 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.[12] Standard 90.2 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 90.2, 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 90.2, 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," 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 90.2, Heating and Cooling Equipment Capacity, describes the requirements for sizing multizone cooling equipment, including 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 ductless 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 90.2.

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 90.2, 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 1,200 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. Costs were confirmed in the field demonstration, Task 4.

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 applications 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)

Number of Zones	Average Heating Capacity Btu/hr	Average Cooling Capacity Btu/hr	Average Cost to Installer
2	18,400	17,700	$2,100[1]
3	26,100	27,900	$3,100[2]
4	36,800	35,400	$4,200[3]

[1] Based on average 1992 cost of 2-zone systems available in U.S.
[2] Based on average 1992 cost of 3-zone systems available in the U.S.
[3] Based on use of two 2-zone systems.

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 (direct labor) 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 direct 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.

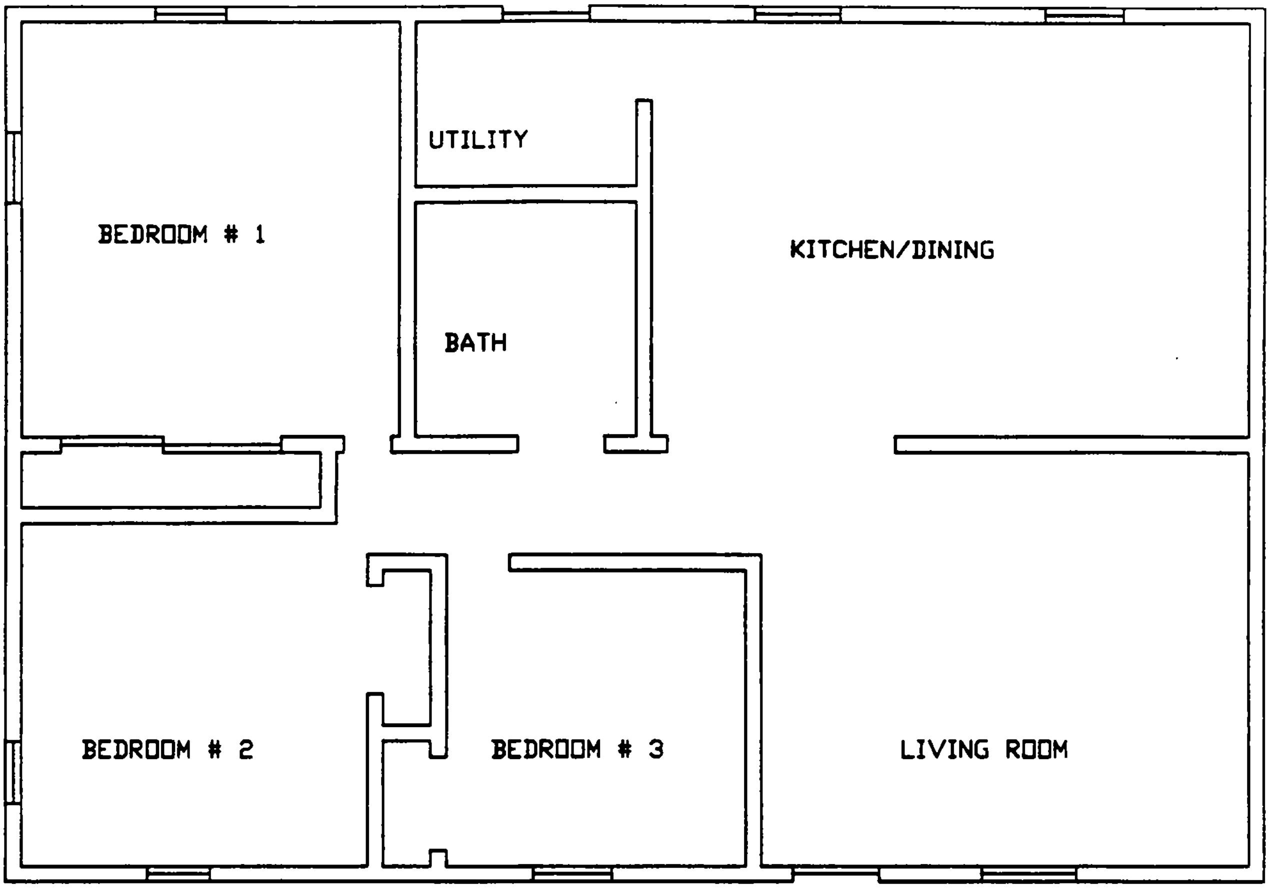


Figure 3. Life-Cycle Cost Example House

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.

- *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) 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.

Table 3
INPUTS FOR LIFE-CYCLE COST EVALUATION
COST TO THE HOME OWNER

	Standard Ducted Heat Pump	Two-Zone Ductless	Three-Zone Ductless	Four-Zone Ductless
HVAC Equipment	$1,800.00	$2,108.50	$3,120.60	$4,217.00
Installation	200.00	250.00	375.00	500.00
GC and Installer Mark-Up	1,200.00	1,415.10	2,097.36	2,830.20
Subtotal	3,200.00	3,773.60	5,592.96	7,547.20
Ducts/Tubes	800.00	150.00	225.00	300.00
Installation	700.00			
60% GC Mark-Up	900.00	90.00	135.00	180.00
Subtotal	2,400.00	240.00	360.00	480.00
Cost to Home Owner	5,600.00	4,013.60	5,957.66	8,027.20
Amount Financed	5,040.00	3,612.24	5,357.66	7,224.48
Down Payment	560.00	401.36	595.30	802.72
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%

- *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	Two-Zone	Three-Zone	Four-Zone
1	$701	$649	$718	$793
2	882	921	888	853
3	1,586	1,565	1,617	1,674
4	2,277	2,197	2,339	2,490
5	2,957	2,818	3,051	3,301
6	3,625	3,428	3,755	4,106
7	4,281	4,027	4,451	4,905
8	4,926	4,615	5,137	5,697
9	5,559	5,191	5,814	6,482
10	6,181	5,758	6,483	7,260
11	6,791	6,313	7,142	8,031
12	7,390	6,859	7,793	8,794
13	7,979	7,395	8,435	9,551
14	8,557	7,920	9,069	10,299
15	9,124	8,436	9,694	11,041

Table 5
HOUSTON LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	Two-Zone	Three-Zone	Four-Zone
1	$742	$681	$751	$825
2	961	984	951	915
3	1,701	1,657	1,710	1,766
4	2,428	2,318	2,459	2,611
5	3,141	2,965	3,198	3,448
6	3,841	3,601	3,928	4,279
7	4,528	4,224	4,647	5,101
8	5,202	4,835	5,357	5,917
9	5,863	5,434	6,056	6,724
10	6,511	6,021	6,746	7,523
11	7,147	6,597	7,426	8,314
12	7,770	7,162	8,096	9,097
13	8,382	7,716	8,757	9,872
14	8,982	8,259	9,408	10,638
15	9,570	8,792	10,049	11,397

Table 6
PHILADELPHIA LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	Two-Zone	Three-Zone	Four-Zone
1	$957	$855	$924	$999
2	1,383	1,323	1,290	1,255
3	2,319	2,155	2,207	2,264
4	3,234	2,966	3,108	3,260
5	4,126	3,759	3,991	4,241
6	4,997	4,531	4,859	5,209
7	5,847	5,286	5,710	6,164
8	6,677	6,022	6,545	7,104
9	7,486	6,741	7,364	8,031
10	8,277	7,443	8,168	8,945
11	9,048	8,128	8,957	9,845
12	9,801	8,797	9,731	10,732
13	10,536	9,450	10,491	11,606
14	11,253	10,088	11,237	12,467
15	11,954	10,712	11,969	13,316

Table 7
SAN FRANCISCO LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	Two-Zone	Three-Zone	Four-Zone
1	$552	$526	$596	$671
2	590	682	648	613
3	1,157	1,214	1,266	1,323
4	1,718	1,740	1,881	2,033
5	2,274	2,259	2,492	2,742
6	2,824	2,772	3,099	3,450
7	3,367	3,278	3,702	4,156
8	3,903	3,777	4,300	4,859
9	4,433	4,270	4,893	5,560
10	4,957	4,755	5,481	6,258
11	5,473	5,234	6,063	6,951
12	5,983	5,706	6,641	7,642
13	6,485	6,172	7,213	8,328
14	6,982	6,631	7,779	9,010
15	7,471	7,083	8,341	9,688

Table 8
TAMPA LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	Two-Zone	Three-Zone	Two-Zone
1	$726	$668	$738	$813
2	931	960	926	891
3	1,657	1,621	1,674	1,731
4	2,371	2,271	2,412	2,564
5	3,072	2,909	3,142	3,391
6	3,760	3,534	3,861	4,212
7	4,435	4,148	4,571	5,026
8	5,098	4,750	5,272	5,832
9	5,748	5,340	5,963	6,630
10	6,386	5,919	6,645	7,421
11	7,012	6,488	7,317	8,205
12	7,627	7,045	7,979	8,980
13	8,229	7,592	8,633	9,748
14	8,821	8,128	9,277	10,508
15	9,401	8,655	9,912	11,259

Table 9
WASHINGTON, DC LIFE-CYCLE ANALYSIS

Total Present Value (sum to year)	Standard Ducted Heat Pump	Two-Zone	Three-Zone	Two-Zone
1	$873	$788	$857	$932
2	1,218	1,193	1,160	1,124
3	2,079	1,963	2,016	2,073
4	2,920	2,717	2,858	3,010
5	3,743	3,453	3,686	3,936
6	4,547	4,173	4,501	4,851
7	5,334	4,877	5,301	5,755
8	6,103	5,565	6,088	6,647
9	6,854	6,238	6,861	7,528
10	7,589	6,896	7,621	8,398
11	8,308	7,539	8,368	9,256
12	9,010	8,168	9,102	10,103
13	9,697	8,783	9,824	10,939
14	10,369	9,385	10,533	11,764
15	11,026	9,973	11,231	12,578

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, the differences attributable to duct losses and efficiency of 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	Typical Two-Zone System	Typical Three-Zone System	Four-Zone System
Down Payment	$560	$401	$595	$803
Principal	28	20	30	40
Interest	503	360	534	721
Maintenance	173	173	173	173
Tax Deduction	(126)	(90)	(134)	(180)
Subtotal	1,138	865	1,199	1,556
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	1,220	1,554	1,912
Houston	1,609	1,254	1,588	1,945
Philadelphia	1,835	1,436	1,770	2,127
San Francisco	1,410	1,092	1,426	1,783
Tampa	1,593	1,241	1,575	1,932
Washington	1,747	1,366	1,700	2,057
Unweighted Average	$1,627	$1,268	$1,602	$1,960

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 that could be conditioned with either a two-zone or three-zone system. Although the ductless systems used for cost comparisons were of adequate capacity to meet the overall demand of the sample home, it was necessary to assume that they were capable of providing adequate thermal comfort to each room of the home. Further research is necessary to confirm this assumption, otherwise some equipment modifications may be required (e.g. allowing one indoor unit to serve two zones with similar demand schedules).

TASK 4: PERFORMANCE EVALUATION

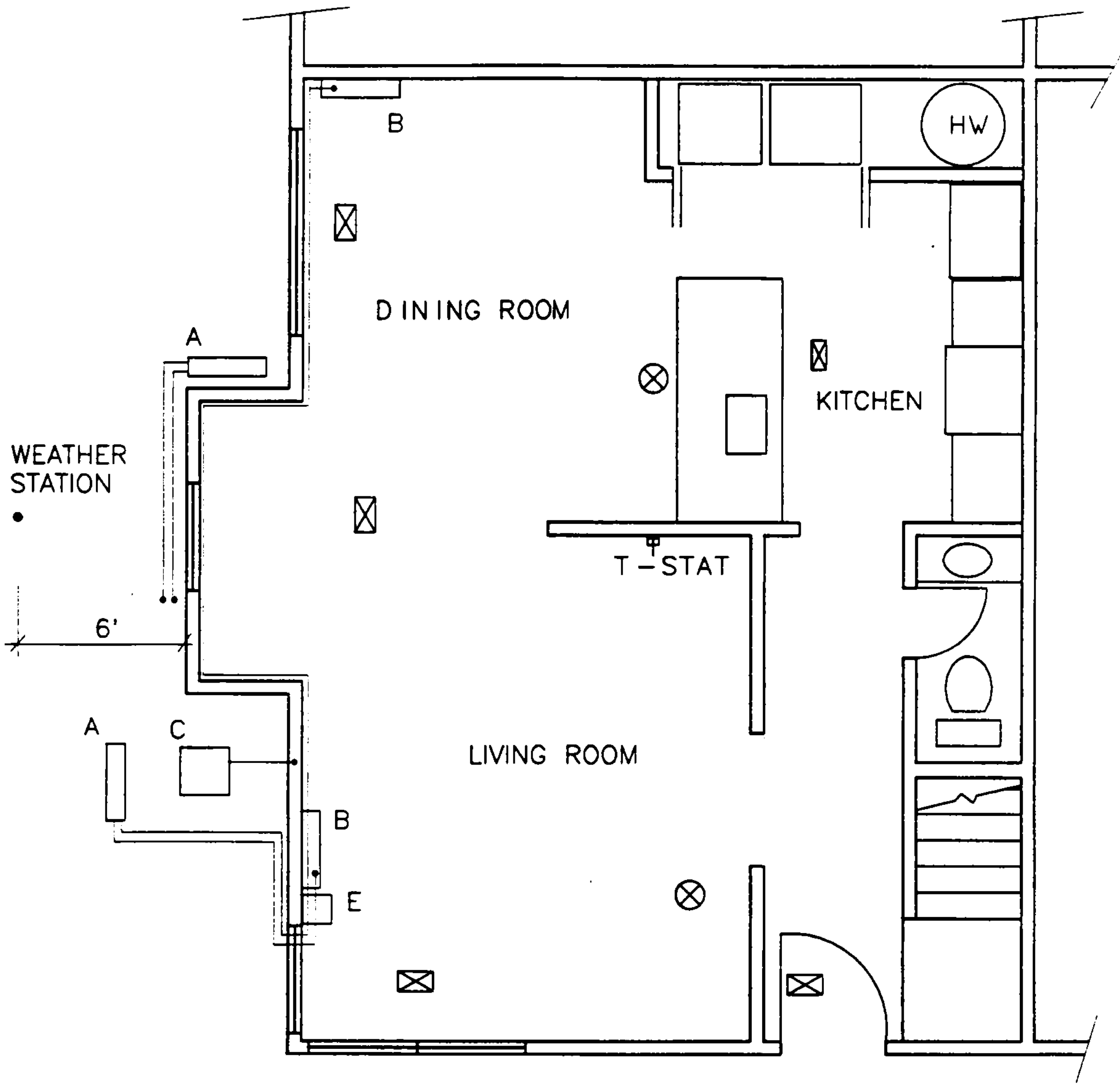
Test Method

The data presented in this section is the result of detailed testing and monitoring of a ductless and a conventional (ducted) heat pump system installed in a demonstration townhouse located in Upper Marlboro, Maryland. Performance data was collected over a portion of the heating season from February through April 1994. Operation of heating systems were alternated to obtain data on both over a range of outdoor temperatures. Constant thermostat setpoints of 72°F were used throughout the tests. The conventional system operated in a single-zone control mode with the thermostat located in the living room on the first floor. The ductless system had four indoor units, creating a four-zone control mode for these tests. An automated data acquisition system was used to collect climate data, indoor comfort data, and energy consumption. The layout of the demonstration home, showing the location of the HVAC equipment and the data acquisition instrumentation, is shown in Figures 4 and 5. The design cooling and heating loads for the demonstration house were calculated to be 16,150 Btu/hr and 28,900 Btu/hr, respectively. Occupant effects were not controlled or documented during the tests. Changes in occupant loads and use patterns, among other things, explains some amount of variation observed in the data. For a period of time during the test, medical needs of an additional occupant required that the front bedroom zone be maintained at a slightly higher set-point temperature.

Equipment Description

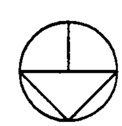
The ductless system used in the demonstration was a two-zone model manufactured by Sanyo-Fisher (outdoor unit model CMH1822 and indoor units KMH0922). Two systems were used to supply four zones. Each zone was served with an indoor unit with a cooling capacity of 8,400 Btu/hr and a heating capacity of 9,000 Btu/hr with a lkw supplemental resistance heater. One indoor unit was installed in each zone, creating four zones of temperature control. This provided a total installed capacity of 33,600 Btuh of cooling and 36,000 Btuh heating for the ductless system. Two indoor units were coupled with one outdoor unit containing two compressors. The efficiency rating for the ductless systems was reported as 10 SEER and 7.0 HSPF. The conventional heat pump system was a Bryant outdoor unit model 541DJ018 with an indoor air handler model 517EN024075, providing an installed cooling capacity of 18,000 Btuh. The conventional system heating capacity was 18,000 Btuh with a 5kw supplemental resistance heater. Heating demand during the test period did not cause operation of supplemental resistance heat on the conventional system. Both systems used single phase, 208/230 volt electrical connections and refrigerant 22 as the heat transfer medium. Each system was installed as would be typical for a house of this size.

The data acquisition system employed an automated datalogger, thermocouples, radiant heat globes, a humidity sensor, a pyranometer for measurement of solar irradiation, and watt-hour meters for measurement of energy consumption of the HVAC equipment. Data stations or comfort stations were distributed throughout the demonstration home as shown in Figures 4 and 5.



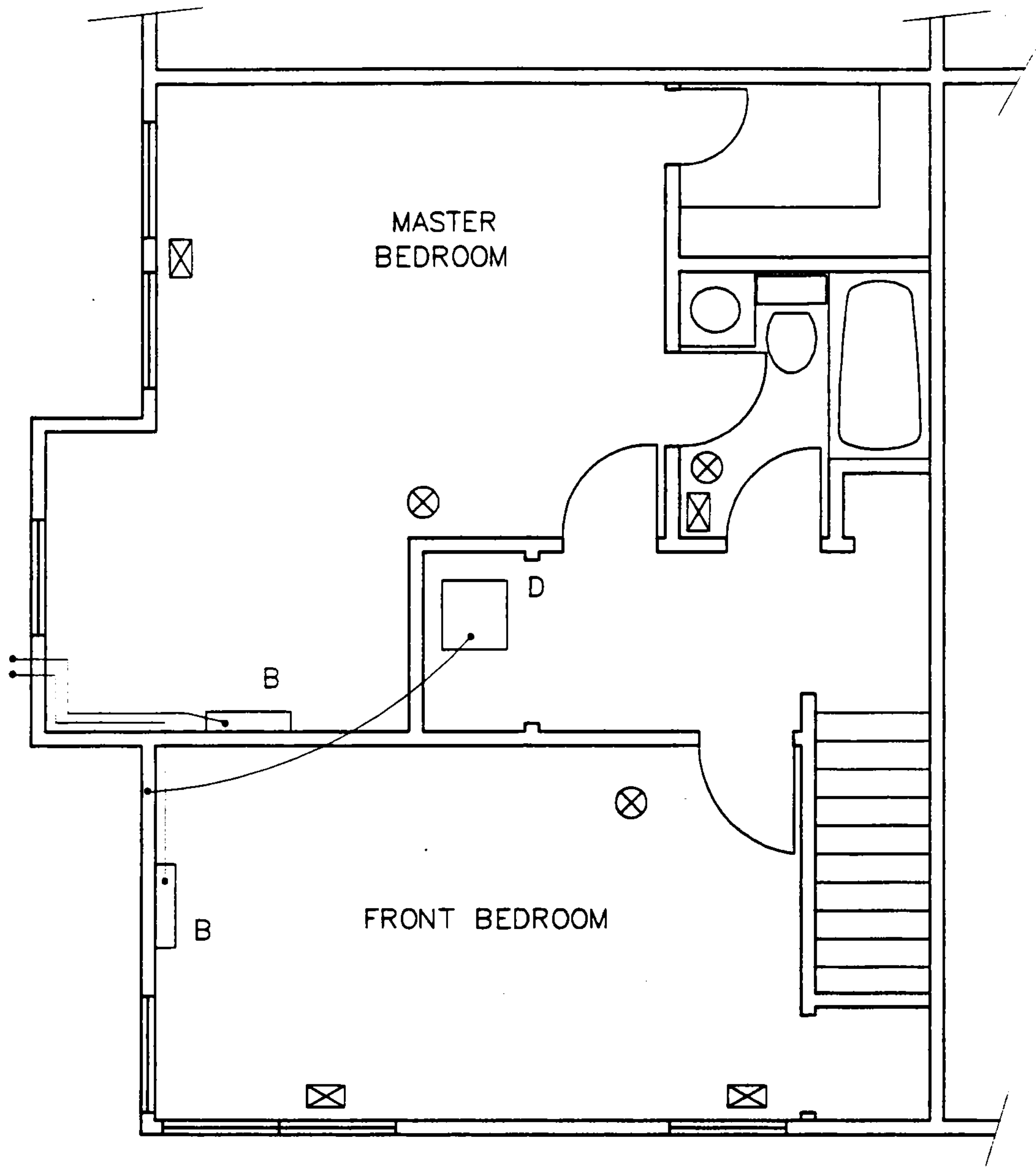
KEY

A = DUCTLESS OUTDOOR UNIT
B = DUCTLESS INDOOR UNIT
C = CONVENTIONAL OUTDOOR UNIT
D = CONVENTIONAL INDOOR UNIT
E = DATA LOGGER
⊠ = CEILING DIFFUSER
⊗ = DATA STATION



NORTH

Figure 4. First Floor Plan of the Demonstration Townhouse



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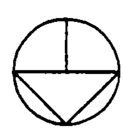

Figure 5. Second Floor Plan of the Demonstration Townhouse

1993-94 Heating Season and Record Year Climate

The Washington, D.C. area heating season spans the 30-week period between October 1 and April 27. Heating energy consumption data taken during the heating season was normalized with the Typical Record Year (TRY) weather data provided by National Climatic Center, Asheville, NC. This process estimates the annual heating energy based on measured rates of consumption over the range of outdoor temperature. The daily average outdoor air temperature for 1993-94 heating season is compared to the TRY data for Washington, D.C., in Figure 6.

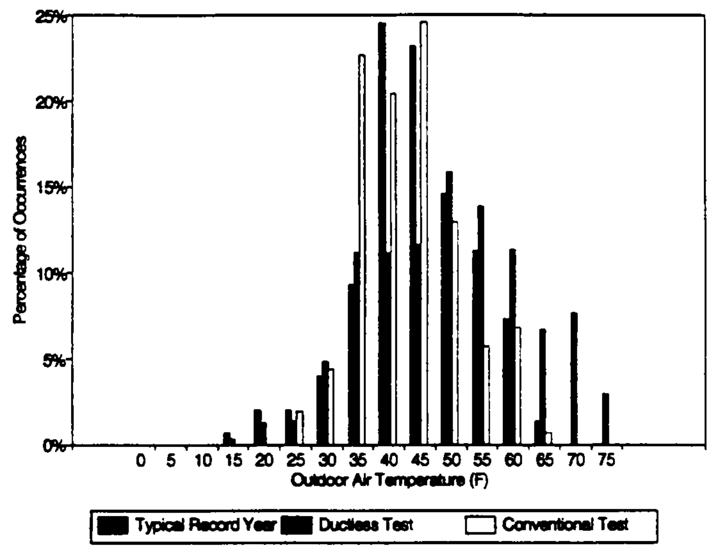

Figure 6. Weather Comparison

Heating Equipment Operating Characteristics

Energy consumption for both the ductless heat pump and conventional heat pump systems was evaluated by comparing average daily temperatures to average hourly consumption. Figures 7 and 8 show the breakdown of each system's energy consumption. The ductless heat pump energy consumption was separated between the upstairs and downstairs units, with the total energy consumption also plotted. Energy consumption for the conventional heat pump unit was separated between the blower consumption and outdoor condensing unit, with the total energy also plotted. The two systems' totals were then plotted and regressed to obtain a linear correlation between outdoor air temperature and energy use, as shown in Figure 9.

The ductless heat pump system apparently used less energy than the conventional heat pump unit. This comparison is not statistically significant because of limited data and a large scatter. However, the improved performance of the ductless system can be attributed to the benefit obtained from zoning the second floor. With a conventional heat pump unit, the second floor is heated whenever there is a call for heat at the first floor thermostat. Due to the hot air rising from the first floor to the second floor, known as the "stack effect," the second floor is often overheated during conventional heat pump operation. Since the ductless heat pump system's indoor units each contain a thermostat, they individually call for heat and the upstairs indoor units only call for heat when necessary.

Improved heating energy distribution by zoning caused a relative decrease in energy consumption with the ductless heat pump system. Differences in system efficiency ratings also explain some of the difference in energy consumption recorded during the test. Duct losses, which would increase energy consumption by the ducted system, are considered negligible for this demonstration home since all ductwork was contained within the floor cavity between conditioned spaces. Energy use of the ductless system could have been further reduced if the available setback control features had been implemented.

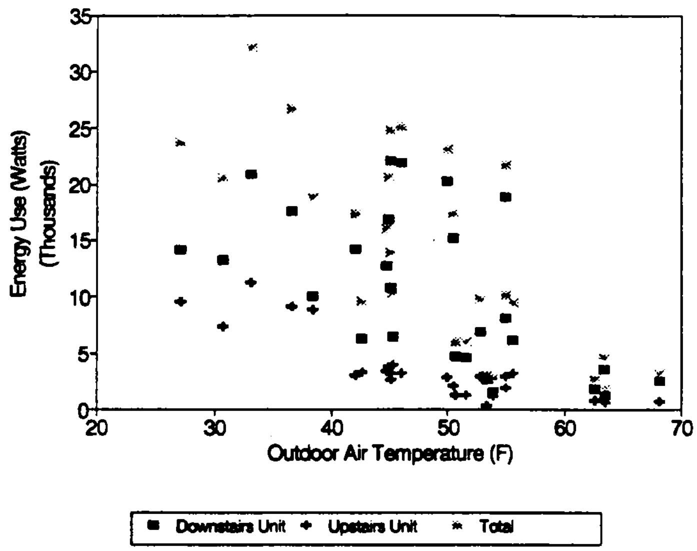

Figure 7. Ductless System Energy Consumption

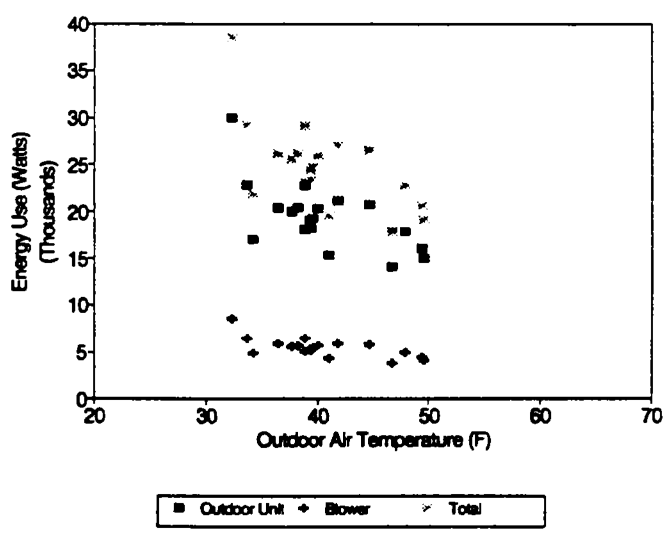

Figure 8. Conventional System Energy Consumption

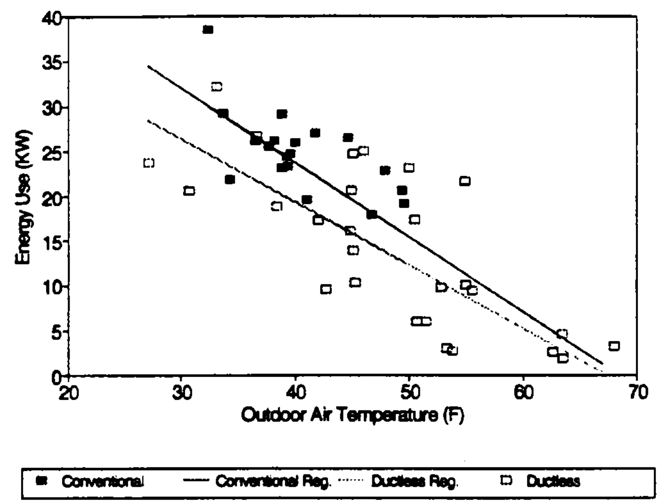

Figure 9. Total Energy Regression for the Ductless and Conventional Systems

Using the energy regressions versus the outdoor air temperature shown in Figure 9, energy consumption for the entire heating season was determined using the TRY data to obtain a seasonal energy consumption plot, shown in Figure 10. For the Washington, D.C. area, it is expected that the ductless heat pump system would use 23 percent less energy than a conventional heat pump system over the course of a typical heating season. This estimate is in agreement with the 20 percent less ductless system energy consumption assumed in the cost evaluation of Task 3.

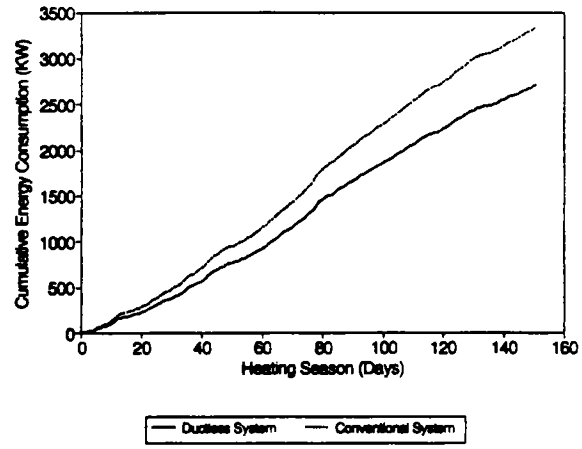

Figure 10
Estimate of Seasonal Energy Consumption
for the Demonstration Home

Operating Cost Analysis

Using an electric power tariff of 7.075 ¢/KWH and the seasonal energy consumption, the operating cost for each system was determined. The operating cost for the ductless heat pump system was predicted to be $192.10, while the cost to operate the conventional heat pump would be $236. When compared with the conventional heat pump, the ductless heat pump system provided an estimated savings of $44 over the course of a typical heating season.

Frequency of Room Temperature Occurrences

Analysis of the frequency of room temperature occurrences by temperature bins is a technique used to determine how well a thermostat maintains the desired setpoint of a HVAC system. Temperature control depends on thermostat location, room size, heating system supply locations, the number and location of doors and windows, and thermostat characteristics. Room temperature frequency was evaluated for both the ductless heat pump and conventional heat pump systems, and is graphically displayed in Figures 11 and 12.

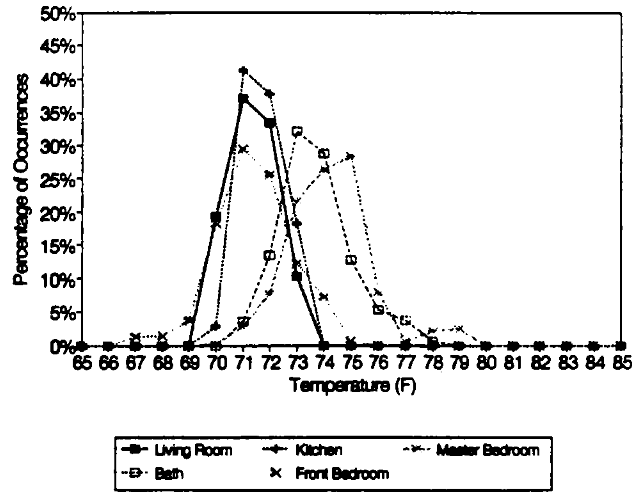

Figure 11
Conventional System Room Air Temperature Frequency

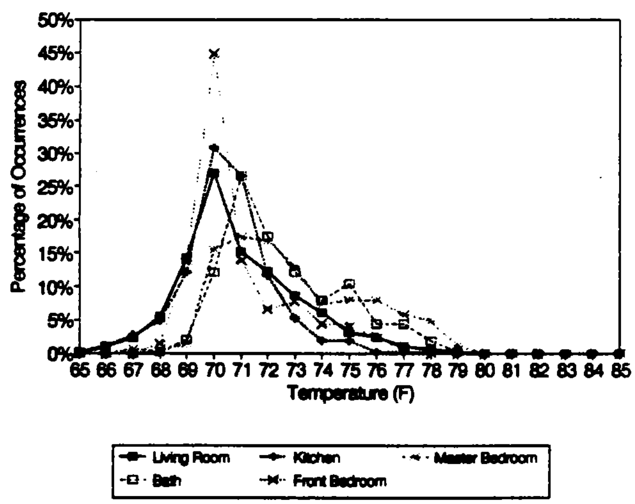

Figure 12
Ductless System Room Air Temperature Frequency

For the conventional heat pump system, the living room and kitchen had tight control as evidenced by most of the observations occurring near the setpoint temperature. Both rooms are located on the first floor, which is also the location of the conventional system thermostat. The bath and master bedroom were warmer than the setpoint, evidence of the overheating and the increased energy consumption discussed earlier.

The ductless heat pump system proved better for temperature control of the upstairs. However, the ductless system, although zoned, was not immune to "stack effect." All three upstairs zones did witness outlying warm temperatures, evidence of some overheating, attributable to "stack effect." While the ductless units will not call for heat during the warm temperature times, they cannot control temperature when the temperature of the zone is above setpoint.

Table 11 lists statistical information regarding the level of temperature control provided to the zones. This information was derived from data presented in Figures 11 and 12. The numerical values represent the interaction and responsiveness between the heating load and thermal mass of the house, the heating system capacity, and control system. For instance, some overheating may have occurred in the upper floors during daylight hours from solar radiation and floor-to-floor stratification. Standard deviation listed in the table is a measure of the tightness of temperature control. Mean temperature is the average temperature for the observations and symbolizes the ability of the system to achieve thermostat setpoint. Note the smaller standard deviations for the ductless system, indicating a smaller range of temperatures in each room than those recorded when using the conventional system.

Table 11
LEVEL OF TEMPERATURE CONTROL

ROOM	Conventional heat pump		Ductless heat pump	
	Mean Temp °F	Std Dev °F	Mean Temp °F	Std Dev °F
Living Room	70.5	2.2	70.9	0.9
Kitchen	70.1	1.7	71.2	0.7
Master Bedroom	72.5	2.5	73.8	1.5
Bath	72.1	2.1	73.2	1.3
Front Bedroom	70.5	1.8	71.0	1.4

Thermal Comfort

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 for ASHRAE. These studies define indices, named predicted mean vote (PMV) and predicted percent dissatisfied (PPD), which characterize thermal comfort in terms of six personal and environmental factors, including metabolic rates, clothing levels, dry bulb temperature, mean radiant temperature, humidity, and room air velocity.

ASHRAE Standard 55-1992[16] considers conditions environmentally thermally acceptable when 80 percent of a given population in a given area is comfortable. A more detailed description of thermal comfort and a Fortran program for calculating the predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) comfort indices, from ISO 7730[17], are provided in Appendix B.

Thermal comfort for both tests was characterized using the PMV and PPD indices. PMV depicts the thermal direction of comfort, shown on the PMV graph as thermally neutral (zero), warm (positive) and cool (negative). PPD index depicts the total effect relative to the population including cool and warm conditions, presenting percentages of people dissatisfied with the thermal environment.

The PMV and PPD indices were calculated for the living room only, which was the location of the relative humidity and mean radiant temperature measurements. This also served as the location of the conventional system thermostat and the ductless system thermostat. The distributions are shown in Figures 13 and 14. Using the comfort indices, the living room and kitchen areas were slightly more comfortable with the conventional system than with the ductless system. Both systems' thermostats were located in these areas, allowing both systems to control the area more efficiently, as evidenced by similar PMV and PPD distributions. Since temperature distributions in all rooms were similar when using the ductless system, it is expected that the PMV and PPD distributions would also be similar for all rooms. For the conventional system with the warmer upstairs temperatures, the PMV would have shifted to the right and a larger percentage of dissatisfied people would have been evident.

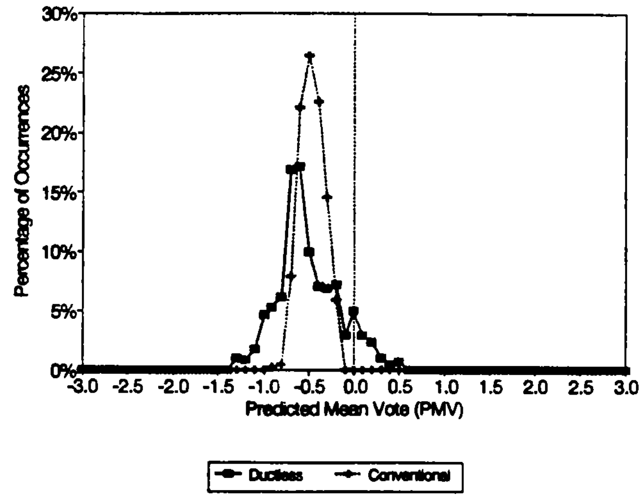

Figure 13
Predicted Mean Vote Distribution

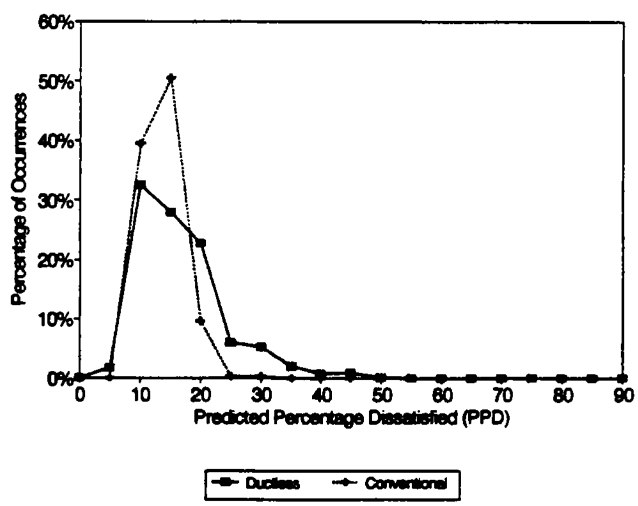

Figure 14
Predicted Percentage Dissatisfied Distribution

Stratification

Air temperature in an enclosed space generally varies from floor to ceiling. If vertical stratification varies more than 5.4°F, thermal discomfort can occur according to ISO Standard 7730-1984. To avoid this type of discomfort, the standard recommends thermal stratification less than 5.4°F, measured at 4-inches and 43-inches from the floor.

Tables 12 and 13 display the occurrences of vertical temperature stratification for the occupied periods. The tables show observations of vertical stratification larger than 5.4°F for the conventional heat pump system in the living room occurred 27 percent of the time, compared with 14 percent of the time for the ductless system. No other room with either system had large stratification problems.

Table 12
CONVENTIONAL HEAT PUMP SYSTEM

Temperature Difference 43"-4"	Living Room	Kitchen	Master Bedroom	Front Bedroom
-5.4°F to 0°F	0%	0%	4%	11%
0°F to 5.4°F	73%	100%	96%	89%
Over 5.4°F	27%	0%	0%	0%
Minimum Temperature Difference	7.7°F	6.2°F	4.2°F	2.8°F
Maximum Temperature Difference	3.5°F	2.5°F	-1°F	-1.3°F
Average Temperature Difference	4.9°F	3.7°F	0.6°F	0.7°F

Table 13
DUCTLESS HEAT PUMP SYSTEM

Temperature Difference 43"-4"	Living Room	Kitchen	Master Bedroom	Front Bedroom
-5.4°F to 0°F	1%	0%	0%	14%
0°F to 5.4°F	85%	94%	99%	86%
Over 5.4°F	14%	6%	1%	0%
Minimum Temperature Difference	13.0°F	6.6°F	7.0°F	3.7°F
Maximum Temperature Difference	-2.7°F	1.6°F	-1.2°F	-1.5°F
Average Temperature Difference	3.5°F	3.5°F	1.9°F	0.9°F

Occupant Impressions

The occupants of the demonstration home were interviewed following the tests to gain insight into the potential concerns of homeowners. It is interesting to note that aesthetics of the indoor units was much less of a deterrent to acceptance of the ductless system following the tests. The occupants were very pleased with the ability to maintain more uniform set-point temperature control with the ductless system and preferred its operation over the conventional, ducted system. The ability to controp set-points by individual zones was an important feature according to the occupants. The occupants were also pleased with the quiet operation of the indoor units in comparison to noise created by the conventional system's indoor unit which was placed in a closet adjacent to the bedrooms. The increased cost to the homeowner (see life-cycle cost analysis of Task 3 for a 4-zone system) was a major deterrent, according to the occupants, that would have caused them to choose the conventional system over the ductless system.

RECOMMENDATIONS

Recommendations based on the information collected under this project can be classified into two 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-dependent demand patterns. Currently available indoor units provide a much higher capacity than required of typical 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 per indoor units should decrease the cost of ductless systems.

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.

Further simplify and improve installation. Flexible, synthetic refrigerant tubing and quick disconnect style fittings should be considered to provide greater ease of installation and removal.

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-dependent demand pattern similar to that of the room that houses the indoor unit.

Decrease capacity of indoor units. Sizes of currently available ductless equipment are generally much greater than required for the typical residential HVAC loads, particularly when considering individual zones. Decreasing indoor unit capacity and size may have only minimal impact on cost, but it may make the units less obtrusive and easier to locate in a home.

CONCLUSIONS

Ductless systems have the capability to be more energy efficient and to provide greater thermal comfort than conventional HVAC systems. They offer an easy method of zonal distribution and thermostat setback control in a house. Ductless systems also permit home owners to set their own operating schedules by controlling setup and setback strategies within different house zones - further improving energy efficiency while allowing for discriminating comfort needs.

From a first cost standpoint, the use of ductless systems in their present form may be justified in some new home construction with simple house layouts having less than three zones which require space conditioning. For most new home applications, the currently available ductless HVAC products do not appear cost effective. As market share increases, it is likely competition will increase with a related decrease in cost. Sales will increase if ductless system manufacturers create and market a ductless system that is more compatible with home construction and competitive with current HVAC products used in new homes.

By reducing first costs, ductless systems can become a more viable alternative in new residential housing. To achieve this objective, manufacturers should consider changing their marketing focus. They also should investigate new designs or even introduce designs used in other countries. Also, perceived market barriers concerning appearance of the system must be overcome by marketing strategies which educate potential buyers on the thermal comfort and energy efficiency benefits of the ductless systems.

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17. ANSI/ASHRAE Standard 55-1981, *Thermal Environmental Conditions for Human Occupancy*, Atlanta, Georgia, 1981.

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

Comfort Definition

Acceptable comfort for humans depends on the range of temperature and related environmental factors for each individual's metabolic heat production and the resultant heat transfer between the individual and the environment. The resulting physiological adjustments and body temperature decide the individual's comfort. The heat transfer is influenced by such environmental factors as air temperature, thermal radiation, air movement, and humidity as well as by such factors as the level of activity and clothing. The net thermal effects have been described using several different techniques.

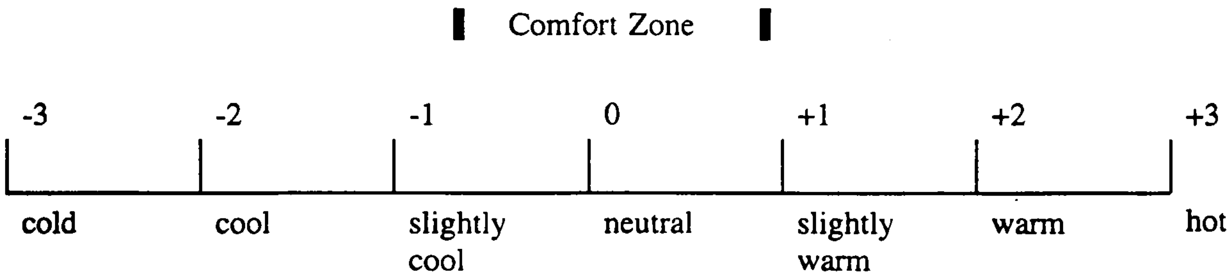
ASHRAE has defined thermal comfort as "that condition of mind which expresses satisfaction with the thermal environment." The comfort region defined by ASHRAE Standard 55-1981 is shown on the psychometric chart presented in Figure B1. The temperature ranges are appropriate for seasonal clothing habits in the United States. The defined comfort region is for sedentary and slightly active people. The winter zone is defined for air speeds less than 29.5 feet per minute (fpm).

Due to differences in individual metabolism and preferences, it is impossible to create a thermal environment that will satisfy everyone simultaneously. The aim of thermal comfort research is to identify conditions that result in thermal comfort for the highest possible percentage of a group. This optimal thermal comfort condition is defined in terms of a comfort equation that accounts for the metabolic rate and radiant and evaporative heat transfer between a human body and the environment.

The Institute for Environmental Research at Kansas State University (KSU) has, under the sponsorship of ASHRAE, 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 thermal conditions of the KSU-ASHRAE envelope had responses nearly identical to those of college-age subjects. In Danish experiments, no significant difference was found between the preferred temperature of younger subjects (mean age 23 years) and elderly subjects (mean age 68 years). Comfort conditions are also independent of the time of day or night. Shift workers preferred the same thermal environment during night work as during the day. 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 of the personal and environmental parameters were varied during the experiment. Each person was asked to rate his comfort level according to a seven-point psychophysical scale. The scale ranged from -3 (cold) to +3 (hot), with 0 representing thermal neutrality. Averaging the comfort levels across the test subjects, a predicted mean vote (PMV) was determined for each set of conditions. In addition, the data were used to predict the percentage of the population that would be dissatisfied with the thermal environment. This 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 (Figure B1).

Figure B1
Predicted Mean Vote Scale



A thermal comfort equation developed by Fanger calculates, for a range of activity and clothing levels, the PMV and PPD for various combinations of air temperature, mean radiant temperature, relative humidity, and air velocity. This iterative comfort equation was incorporated into a Fortran program presented at the end of this appendix. The formula to convert PMV to PPD is

$$PPD = 100 - 95 * e^{-(0.03353*(PMV)exp4 + 0.2179 * (PMV)exp2)}$$

Instrumentation at the demonstration house collected data on relative humidity, dry bulb temperature, and mean radiant temperature. A value of 15 fpm for room air velocity is assumed because air moving at room air velocities is below the measurement threshold of commercially available air flow transducers. Personal factors used in determining PMV were an activity level of one met (58 watts/square meter) and a clothing level of one clo (trousers and sweater). The level of clothing corresponding to comfort levels are shown in Figure B3.

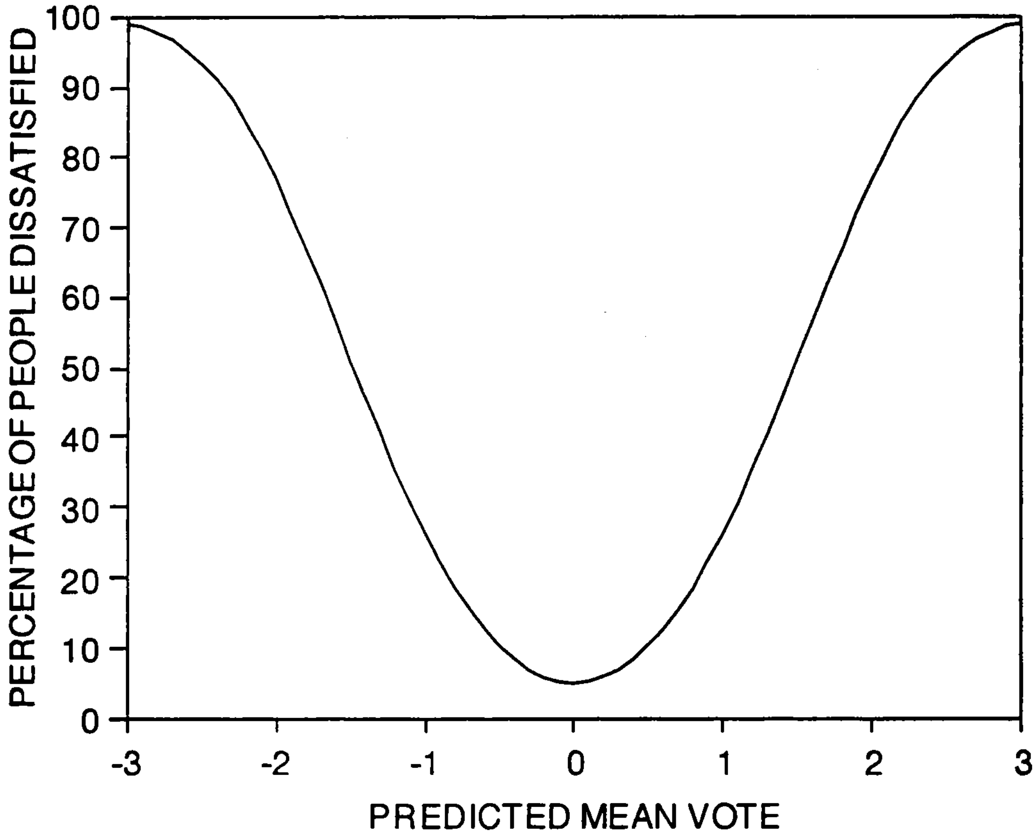


Figure B2
Percentage of People Dissatisfied (PPD)
as a Function of Predicted Mean Vote (PMV)

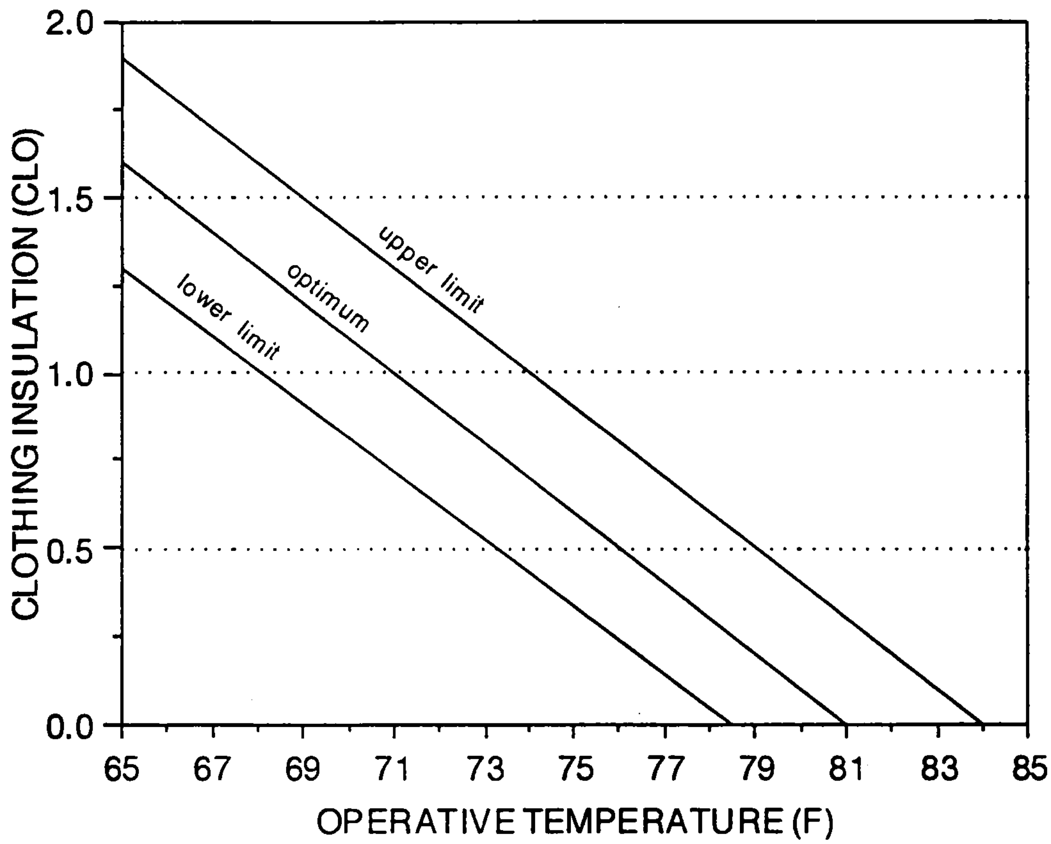


Figure B3
Clothing Level Corresponding to Optimum Comfort Levels

Table B-1
Factors Influencing Thermal Comfort

<u>Activity Level (Metabolism)</u> - Metabolic rate (met rate) is the internal body heat created by energy released in the human body per unit of time. Metabolism is what makes comfort so much a function of the individual.

<u>Clothing Level (clo)</u> - Clothing, because of its insulation value, is an important modifier of body heat loss and comfort. Typical indoor winter clothing has a range from 0.8 to 1.2 clo. During the winter, wearing heavy slacks, a long-sleeve shirt, and a sweater gives a clo value of about 1, while a pair of shorts has a clo level of about 0.05. The operative temperatures and the clo values corresponding to the optimum comfort level are given in Figure B2.

<u>Dry Bulb Temperature</u> - Dry bulb temperature (t_{db}) is the simplest practical index of cold and warmth under ordinary room conditions. For average humidity, t_{db} is significant in judging comfort under cold conditions. When heat and humidity affect the efficiency of body temperature regulation by sweating, the significance of t_{db} is more limited. For slightly active people (<1.2 mets) at 50 percent relative humidity, the optimum operative temperature is 71°F and the operative temperature range for 80 percent thermal acceptability is 68°F to 74.5°F.

<u>Mean Radiant Temperature</u> - Mean radiant temperature (t_r) is the uniform black body surface temperature with which a person (also assumed a black body) exchanges the same heat by radiation R as in the actual environment. In a home environment where air movement is low, the operative temperature is approximately the average of air temperature and mean radiant temperature. Operative temperature (t_o) is the uniform temperature of an imaginary enclosure with which a person exchanges the same dry heat by radiation and convection (R + C) as in the actual environment.

<u>Humidity</u> - Humidity is described in terms of dew point in Figure B1. The dew point should be between 35°F and 62°F for the comfort region occupied by sedentary people. The limits of humidification depend on comfort, respiratory health, mold growth, and other moisture-related problems. Humidification in the winter may need to be limited to prevent condensation on building surfaces.

<u>Room Air Velocity</u> - There is no minimum air movement required for thermal comfort in the acceptable temperature range of Figure B1. The average air movement in the occupied zone should not exceed 30 fpm. If the room temperature is less than optimum, then the maintenance of low air movement is important to prevent drafts. Anemometer readings of below 50 fpm are highly variable and only relatively accurate. At low air movement, it is difficult to distinguish between air movement resulting from free and forced convection and that caused by body movements.

Fortran Program for Calculating PMV and PPD Indices (ISO, 1983)

```
C         CALCULATION OF THE PMV AND PPD INDICES
C
C         FORTRAN IV PROGRAM
C
      Program PMVCAL

      CHARACTER*15 TIME
      REAL M,ICL,MW
      Real*8 PwC(6)

c                   Activity level : 1 Met
      DATA M   /58.0/
c                   External work  : 0
      DATA W   /0.0/
c                   Clothing level : 1 Clo
      DATA ICL /0.155/
c                   Air velocity   : 15 fpm = 0.0762 m/s
      DATA VAR /0.0762/
      DATA PwC /-10440.4,-11.2946669,-0.02700133
     *      ,0.1289706e-4,-0.2478068e-8,6.5459673/

c
c-----------------Open input and output files
c

      PRINT*, 'ENTER INPUT FILE NAME'
      READ*, NAMEIN
      PRINT*, 'ENTER OUTPUT FILE NAME'
      READ*, NAMEOUT
      OPEN(5,file=NAMEIN,status='old')
      OPEN(6,file=NAMEOUT,status='new')

      WRITE(6,698)'TIME','PMV','PPD'
698    FORMAT(7x,a4,9x,a3,5x,a3)

c
c-----------------READ INPUT DATA
c

300     READ(5,599,END=999) time,TAF,TRF,RH
599     format(A15,3f11.4)
```

```
c
c-------------------Calculate PA from RH
c

      TAR= TAF+459.67
      Pws= EXP( PwC(1)/TAR + PwC(2) + PwC(3)*TAR + PwC(4)*TAR**2
     *         + PwC(5)*TAR**3 + PwC(6)*LOG(TAR) )
      PA= 68.9*RH*Pws
      TA= (TAF-32)*5/9
      TR= (TRF-32)*5/9
      EPS=0.00015
      MW=M-W

C
C-------------------COMPUTE THE CORRESPONDING FCL VALUE
C

      FCL=1.05+0.645*ICL
      IF (ICL.LT.0.078) FCL=FCL-0.05*.645*ICL
      FCIC=ICL*FCL
      P2=FCIC*3.96
      P3=FCIC*100
      TRA=TR+273
      TAA=TA+273
      P1=FCIC*TAA
      P4=308.7-0.028*MW+P2*(TRA/100)**4

C
C-------------------FIRST GUESS FOR SURFACE TEMPERATURE
C

      IF ((6.45*ICL+0.1) .ne. 0)  THEN
        TCLA=TAA+(39.5-TA)/(3.5*(6.45*ICL+0.1))
      ELSE
        write(*,*) 'Attempted divide by zero, 6.45*ICL+0.1 = 0'
        TCLA= 0
      ENDIF
      XN=TCLA/100
      XF=XN
      HCF=12.1*SQRT(VAR)
      NOI=0
```

```
C
C COMPUTE SURFACE TEMPERATURE OF CLOTHING BY ITERATIONS
C

100   XF=(XF+XN)/2
      HCN=2.38*ABS(100*XF-TAA)**0.25
      HC=AMAX1(HCF,HCN)
      IF ((100+P3*HC) .ne. 0)  THEN
        XN=(P4+P1*HC-P2*XF**4)/(100+P3*HC)
      ELSE
        write(*,*) 'Attempted divide by zero, 100+P3*HC = 0'
        XN= 0
      ENDIF
      NOI=NOI+1
      IF (NOI.GT.150) GOTO 200
      IF (ABS(XN-XF).GT.EPS) GOTO 100
      TCL=100*XN-273

C
C-------------------COMPUTE PREDICTED MEAN VOTE
C

      PM1=3.96*FCL*(XN**4-(TRA/100)**4)
      PM2=FCL*HC*(TCL-TA)
      PM3=0.303*EXP(-0.036*M)+0.028
      PM4=0.0
      IF (MW.GT.58.15) PM4=0.42*(MW-58.15)
      PMV=PM3*(MW-3.05*0.001*(5733-6.99*MW-PA)
     * -PM4-1.7*0.00001*M*(5867-PA)-0.0014*M*(34-TA)-PM1-PM2)
      IF (ABS(PMV).GT.3) GOTO 200
      GOTO 240

200   PMV=999999.999
      PPD=100.
      GOTO 250

240   PPD=100-95*EXP(-0.03353*PMV**4-0.2179*PMV**2)
250   IM=M
      IW=W
      IPA=PA
```

```
c
c--------------------Write Results
c

      WRITE(*,700) TIME,IM,IW,ICL,TA,TR,VAR,IPA,PMV,PPD
700    FORMAT(1H /1x,A15,2X,I3,4X,I2,3X,F5.3,3X,F4.1,3X,F4.1,3X
     * ,F4.2,3X,I4,6X,F4.1,3X,F4.1)

      write(6,699) time,pmv,ppd
699    format(1x,A15,2f8.2)

c
c--------------------Go back to top for next case
c
     GO TO 300

c
c--------------------Come here when done
c

999   STOP
     END
```