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Zone Conditioning in a California Foothill House

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December, 1993

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Executive Summary

The principal focus of the reported research is the performance of the installed zoned air distribution system in a house located in the foothills northeast of Sacramento California. The 297 m^2 (3200 ft^2) two story house contained a central air conditioner and an air distribution system with four dampered supply duct legs. The air conditioning system included a two speed fan and two speed compressor, with the air handler placed inside a closet and almost all the ducts located inside the building envelope. The uninsulated sheet metal ducts ran inside a space between stories and in interior walls. The performance parameters examined included: 1) duct leakage, 2) duct conduction, 3) zoning performance and 4) equipment efficiency impacts.

The duct system was found to have a somewhat higher specific duct leakage area (1.3 cm^2 duct leakage per m^2 of house floor area) compared to other housing stock in California (1.0 cm^2/m^2), but was much tighter in comparison with other houses with sheet metal ducts (1.9 cm^2/m^2). Nevertheless leak sealing efforts could have been improved with direct leakage measurements at the time of duct installation. Most importantly, the location of the ducts prevented almost all of the duct leakage from being lost to outside the conditioned space. The actual leakage to outside was 0.2 cm^2/m^2, which is an 80% improvement over common California construction.

Measurements of air flowrates revealed that large portions of the total system airflow was through duct system leaks. When the house was conditioned as a single zone, 83% of the supply air went to and 63% of the return air came from the intended zones and the remainder consisted of supply and return duct leakage. These fractions dropped off dramatically when conditioning in fewer zones, to 58% supply and 19% return air flow when conditioning in two zones and to 57% and 20% respectively when conditioning in one zone only. The small fraction of return airflow was attributed to the open configuration of the house and the lack of return duct dampers in each zone. Installing an artificial zone separation and return duct dampers increased the return air fraction for conditioning in one zone to 44%.

In spite of their placement inside the building envelope, supply duct conduction losses (20%) were not significantly lower than that found for houses with ducts in the attic or crawlspace (23%). This was due to the long runs of uninsulated sheet metal ducts in the house. On the other hand, the conduction losses were not to outside, as is usually the case. The major impact of the losses in this house was simply to make zoning more difficult to attain.

The air distribution system's ability to zone was strongly influenced by thermal stratification in the house. When the upstairs zones were setup 5 °C cooler than the downstairs zones, 18% of the desired temperature difference was realized. In another test, 70% of the desired temperature difference between zones was realized when the downstairs zones were setup 2.7 °C cooler than the upstairs zones. When the house

was conditioned as a single zone with all thermostats at the same setpoint, a 1.2 °C difference between upstairs and downstairs temperatures was obtained. The results indicated that the air distribution system could not overcome house thermal stratification when cooling only in upstairs zones. Conversely, stratification improved the zoning performance when cooling only in the downstairs zones. Also contributing to better zoning performance downstairs was the communication with duct leakage and conduction losses in the interstitial space through vented access panels between the first floor and the interstitial space.

Two ways of characterizing distribution system performance are 1) how much of the conditioned air is delivered at the registers (thermal delivery efficiency) and 2) how much of the conditioned air ultimately reaches the conditioned space (distribution efficiency). The thermal delivery efficiency (sensible cooling only) was 64% for conditioning in all zones. This was comparable to that for typical California houses, 67%, however it failed to demonstrate that the losses did not escape the conditioned space. On the other hand the distribution efficiency showed the substantial benefit of placing the ducts inside the conditioned space. For the test house, the distribution efficiency was 98%. For a typical California house, the distribution efficiency is approximately the same as its thermal delivery efficiency. The thermal delivery efficiency is a good indicator of the duct system's ability to zone. Specifically, low thermal delivery efficiency hampers zoning performance. When conditioning in the upstairs zones, the thermal delivery efficiency was reduced to 50%. For these cases 18% of the desired temperature difference between zones was realized.

The air conditioning system had an air bypass damper for capacity control. The bypass damper opened when conditioning in one of the four zones. This decreased return air plenum temperatures by 5 °C and reduced the capacity of the air conditioner. In effect, capacity control was achieved by reduction of the air conditioner efficiency. Air distribution system pressures were not reduced significantly when the bypass damper was open, thus duct leakage remained high when conditioning only a fraction of the house.

In conclusion, two major points were made concerning the test house. The first was that substantial energy benefits were realized by placing the ducts inside the conditioned space. The second was that the energy benefits from zoning the house were not realized, primarily due to thermal stratification and the open floor plan in the house. Secondary impacts lowering zoning performance were the lack of return duct dampers and leakage and conduction losses in the air distribution system. Utility programs or building standards promoting zoning as a means of conserving energy or reducing peak power demand should be aware of the many potential pitfalls that can arise with zone conditioning, particularly with dampered air distribution systems.

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1.0 Introduction

Since the turn of the century, centralized heating and cooling systems have enjoyed general acceptance in residential houses in the U.S. Today, approximately 50% of the houses in California have installed centralized space conditioning systems, a large fraction of which are controlled by a single thermostat. Before these centralized systems became prevalent, use of localized heaters for each zone in the house was the norm. Coming full circle in an effort to meet energy conservation needs and flexibility in home space conditioning, residential zone conditioning systems are again receiving more attention.

Zone conditioning systems, which are common in commercial buildings, provide heating and cooling to those parts of the house where required. This is similar to the use of local heating and cooling equipment. Still present however, are the advantages of a centralized system, which include increased energy efficiency, more convenience and easier system maintenance. Residential zone conditioning systems use separate thermostats in each zone, which provide closer monitoring of temperature variations and faster response to heating and cooling needs there. This results in an improvement in the thermal comfort of the house. Because the multiple zone system need only heat or cool that part of the house where required, savings in the house overall energy use is also expected.

Previous studies have focused on the energy savings in residential zone conditioning strategies. In a study of a residence in Knoxville Tennessee, Levins (1989) calculated a 9.7% reduction of heat pump heating load when 21% of the house was removed from the air distribution system by closing internal doors and sealing the supply and return registers behind those doors. This simple zoning strategy resulted in 18% further savings when 41% of the house was closed off. The heat load reduction was nearly doubled when the heating method used was electric resistance. Paradoxically, in the cooling season, the Levins study revealed no reduction in electrical usage or cooling load for the same zoning strategy. Using a two speed compressor and a variable speed fan in a zoned air distribution system with no bypass duct and a temperature setup schedule, Oppenheim (1992) found the energy use under zoning in a Maryland house to be 84% of the energy use for the house when operated as a single zone. Adding fan overrun reduced this percentage to 75%.

Zoned central dampered air distribution systems are installed in many different ways. Generally, they consist of a central furnace/air conditioning unit and fan and dampered supply ducts leading to each house zone. Ideally, each house zone is separated from the other zones by the closing of internal doors. The California Energy Commission (CEC, 1988) recommends a maximum open area between zones of 3.7 m^2. This is larger than most open doorways. The house is divided into two or more zones, each with separate thermostat control to regulate the flow of conditioned air to that zone. Many houses are divided into only two zones, the living zone and sleeping zone. The CEC requires use of programmable thermostats for setback and setup temperature schedules in the heating and cooling seasons. The CEC also requires return ducts to each zone. Although each return duct should have a controllable damper back to the central unit (Modera, 1990), the existence of return dampers in residential systems is rare, and in fact is not required for Title 24 energy compliance credit. Other possibilities for zoned systems include incorporating variable speed fans, variable capacity heating and cooling equipment or a dampered bypass duct.

When zoning with central heating and cooling equipment the performance of the air distribution system is crucial for actual reduction of energy use and maintenance of thermal comfort. Energy losses in the ducts become significant when conditioning in only one or two zones. If the losses are large enough, energy savings gained by the use of zoning can be eliminated. Energy losses in the air distribution system are primarily conduction losses due to inadequately insulated ducts and leakage losses due to an imperfectly sealed duct system. Modera et. al. (1992) found that in simulations, one-third of the heating bill in a recent vintage ranch house in Sacramento with attic supply ducts and crawlspace return ducts was caused by duct inefficiencies. For the cooling season in the same house the percentage was 23%, increasing to 40% when the return ducts were also placed in the attic. Lambert and Robinson (1989) concluded in a field study of duct leakage impacts on 20 houses built after 1980 that a 12% average of heating system efficiency was lost due to duct leakage.

This report examines the actual performance of a residential dampered air distribution system. The residence is located in the foothills about 20 miles northeast of Sacramento. The house layout and air distribution system configuration is described and compared with other zone conditioned and conventionally conditioned houses. Descriptions of the tests performed and their results during the cooling season of 1992 are presented. The analysis focuses on the house and air distribution system performance under different zoning configurations and the zonal temperature response to thermostat setpoints. Factors influencing the zoning performance are also examined. In the house, air stratification and inter-zonal air mixing have a significant impact. The impact of duct leakage and conduction losses under zoning are examined. Other factors influencing the zonal air distribution system performance include the use of an installed dampered bypass duct and the impact of putting the ducts inside the building envelope.

1.1 House Description

The test house had a two-story open-floor-plan with a lower floor area of 167.5 m^2 (1803 ft^2) and upper floor area of 112.5 m^2 (1211 ft^2) for a total floor area of 280 m^2 (3014 ft^2). Downstairs rooms consisted of the entryway, living room, dining room, kitchen, breakfast nook, family room, laundry room, powder room, bathroom 2 and bedroom 4 (also called the den). The sunken living room shared its ceiling with the upper floor, as did the entryway. In fact, part of the upper floor hall was a bridge over the living room/entryway/staircase connecting the master bedroom, bedroom 3 and bathroom 3 to bedroom 2. There was also a large bathroom off of the master bedroom. In addition to the living spaces, there were also storage and utility closets downstairs. One closet off the hall entryway contained the computer and related equipment that monitored and controlled the HVAC system, appliances, entertainment systems and other house features. Another closet off the dining room contained the HVAC unit and manual thermostat controls for each house zone. Temperature sensors mounted in the walls of each house zone were monitored by the installed data acquisition system and thermostat controls. Appendix A contains diagrams of the house layout and configuration of the air distribution system.

The total floor area excluded the garage, which had been converted into a display area for visitors and was conditioned by a separate HVAC unit. The house volume was 820 m^3 (28965 ft^3) and it had 43 m^2 (458 ft^2) of external windows and doors. There was R22 batt insulation in the wall and floor cavities of the envelope. In addition, there was 1″ of R4.8 foam sheathing on the exterior of the house. The attic was insulated with cellulose with an R-value of 38.

The main HVAC unit in the house delivered conditioned air to a zoned air distribution system. There were four dampered supply duct legs connected to the supply plenum. The opening and closing of the dampers was controlled by the computer in response to the thermostat settings, or by the manual controls located in the furnace closet. The supply registers connected to each dampered duct leg are given in Table 1. Zones 1 and 2 were downstairs, zones 3 and 4 upstairs. All of the supply registers in zone 1 were located in the ceiling. In zone 2 the living room and hall entryway registers were located high on the walls, while bedroom and bathroom 2 supply registers were in the ceiling. All supply registers in the remaining zones were located high on the walls.

TABLE 1. Location of supply zone registers[a]

Supply Zone 1	Supply Zone 2	Supply Zone 3	Supply Zone 4
Family Room*	Living Room East*	Master Bedroom*	Bedroom 2*
Dining Room*	Living Room West	Master Bathroom	Top of Entryway*
Breakfast Nook*	Bedroom 4*	Bedroom 3*	Bathroom 3
Kitchen	Hall Entryway		
Laundry Room	Bathroom 2		

[a] asterisks indicate which supply register temperatures were monitored

There were four return ducts in the house, none of which were dampered. The main return duct register was in the dining room ceiling near the closet containing the HVAC unit. Another large return duct was located in the wall approximately 4.5 m (15 ft.) above the floor in the living room. There were two small return ducts. One of these return duct registers was located on the wall inside the master bedroom approximately 5 cm from the ceiling and the other register was in the hall just outside the master bedroom door at the same level. None of the return ducts were specifically assigned to house zones, although the two small returns were in close proximity to zone 3. Duct and register dimensions are given in Appendix A.

The important features of the installed heating/cooling equipment for zone conditioning were a two speed compressor and a two speed fan. It was a split system, with the compressor located outside on the east side of the garage. A bypass duct with a variable position damper was connected between the supply and return plenums as part of the zoning system. The purpose of the bypass damper was to relieve pressure buildup in the supply plenum when two or more supply zone dampers were closed. The bypass duct circulated air back to the return plenum. This process had significant adverse energy impacts on system performance, which will be discussed in this report.

This house was unusual in that all air ducts except one were located inside the building envelope between the two floors of the house. This is atypical in that most air distribution systems in California single family houses are located either in the attic or crawlspace. In this house, losses from the ducts due to leakage and conduction were still within the building envelope and were recovered by the house whereas losses from attic ducts were not. In order to gain access to the four supply duct dampers, four large register grilles were used. These grilles were located in the dining room ceiling near the furnace closet and had air filters installed in them blocking the view into the interstitial space. There was a similar grille in the computer closet for access to the bypass duct damper. The placement of these grilles provided air flow pathways between the duct chaseway and the house interior.

The ducts were made of spiral sheet metal. There was no insulation on the outside of the ducts. One duct approximately 1.3 meters long ran outside the building envelope and was connected to the breakfast nook supply register. Insulation of at least R4 was observed on this duct. Also incorporated in the duct system was an economizer which operated off of the return plenum. For our tests, the economizer was not used. The economizer inlet register was located outside by the front door and the outlet register was in the attic. There was also an installed exhaust only mechanical ventilation system which could be run on a time schedule. It was never on during testing.

2.0 Methods

In order to compare results of our tests with results from other studies the house was divided into "living" and "sleeping" zones. Because of the configuration of the installed zone conditioning system, there was not much choice in assigning house zones as living and sleeping zones. A natural choice for living and sleeping zones was to split the house into upstairs (sleeping) and downstairs (living) zones.

However, because of the open floor plan, dividing the house in this way created an open area of 24 m^2 between the zones, which was much greater than the CEC limit (3.7 m^2). Another choice of zoning assigned only the master bedroom and bedroom 3 (zone 3) as the sleeping zone, with the remaining zones belonging to the living zone. For this assignment the open area (2.6 m^2), was under the CEC limit. It should be noted that in all tests the supply register in bathroom 3 was sealed. This allowed all of the supply and return registers in the rooms connected to the short hallway upstairs to be assigned to the sleeping zone, simultaneously assigning all other supply and return registers in zones 1, 2 and 4 to the living zone. To simulate the effect of complete zone separation, an artificial barrier was constructed at the hallway opening. Simulations of the effect of return duct dampers on zone conditioning were made with the artificial separation in place.

Tests performed on the house included measurements of the envelope and duct leakage (total and to outside), air flows out of supply and into return registers for each zone configuration, long term monitoring of air temperatures and operational pressures in the duct system, air temperatures in the attic, crawlspace, duct chaseway and outside, as well as monitoring of power demand by the compressor and air handler fan. This data was used to determine the magnitude of leakage and conduction energy losses from the distribution system, and the zonal temperature response to thermostat setpoints for each configuration. Table 2 lists the zone configurations for which complete measurements were made. The following sections describe the measurement methods for register air flows, envelope and duct leakage and thermal performance testing of the zoned system.

TABLE 2. Operation mode descriptions

Mode	Supply Damper Position				separation between zones	living zone returns	sleeping zone returns
	zone 1	zone 2	zone 3	zone 4			
A	open	open	open	open	no	unsealed	unsealed
B	closed	closed	open	open	no	unsealed	unsealed
C	closed	closed	open	closed	no	unsealed	unsealed
D	closed	closed	open	closed	yes	unsealed	unsealed
E	closed	closed	open	closed	yes	sealed	unsealed
F	open	open	closed	open	yes	unsealed	sealed

2.1 Register Flow Tests

Measurements of airflow into the return registers and out of the supply registers were made for each mode with a flow capture hood. Such hoods measure flows more accurately in commercial applications where the air flowrates are higher than in residences. To improve the accuracy of measurements, the flowhood was recalibrated in the laboratory with a more accurate pressure sensor. During tests, time-block averaged samples of the pressure across the sensing element were made for each measurement. This significantly reduced scatter in the pressure measurement, and improved the accuracy of the flow measurement.

2.2 House and Duct Leakage Tests

Envelope leakage was determined with the use of a blower door and the testing procedure closely followed ASTM Standard E779 for pressurization only. The procedure differed from the standard in that the duct system was sealed from the house envelope by sealing the registers. Pressures in the ducts were maintained the same as the house pressure by a separate fan, called the duct tester, which was connected to one open register from the house interior. This allowed for the simultaneous determination of duct leakage to outside. Measurements of house leakage were made with the duct tester fan connected to the supply and return sides of the air distribution system separately, in each case the two sides were separated by a seal at the air handler. Beginning at 12 Pa, the house was pressurized in increments of approximately 12 Pa up to 50 Pa. Several datapoints at each house pressure were recorded with the aid of a data acquisition system and an interactive computer program in order to collect a large sample of points for later regression analyses.

Duct leakage to outside was determined during envelope leakage testing by determining the airflow through the duct tester fan at each house pressure. Duct tester fan speed was adjusted until duct pressures matched house pressures. Duct tester airflow and duct pressure were read from the magnahelic gauges on the unit. The procedure was the same for both the supply and return sides. In each case, the untested side was completely sealed from the tested side of the air distribution system and house interior. An operator initiated program collected several datapoints at each house pressure to insure a good regression analysis. Possible sources of duct leakage to outside included one supply duct which was not located inside the building envelope and the economizer inlet and exhaust vents, both connected to the return side of the duct system.

Total duct leakage was determined with the duct tester connected to the supply side and the return side separately. The blower door was not operated during these tests. Duct leakage for each leg of the supply zones was also measured. The duct tester feed was connected to the dining room supply duct and the duct tester flow and duct pressure were measured for zone 1 ducts by keeping the zone 1 damper closed. The zone 1 damper was then opened and the test repeated for supply zone 1 and the supply plenum together. For this test all other supply zone dampers and the bypass damper were kept closed. Zone 2 and all remaining supply zones were measured by sequentially opening their supply dampers and repeating the test. Leakage areas for each part of the supply side were determined by subtraction. Total supply side leakage was measured with all dampers open except the bypass damper.

2.3 Air Distribution System Performance Tests

The air distribution system performance tests were set up to measure the temperatures, pressures and power demand of the house and air distribution system during the modes of operation shown in Table 2. Thermocouples were placed directly behind the grilles in each of the supply registers indicated in Table 1. Thermocouples were also placed in the master bedroom and dining room return registers, the return plenum, the duct chaseway, as well as in the attic, crawlspace and outside. An averaging thermocouple with nine junctions was used to monitor the supply plenum temperature. The outside thermocouple was aspirated and shielded from direct sunlight and bright surfaces. Static pressures in the supply plenum, return plenum, each leg of the zoned system, inside the house and outside the house were also monitored. The outside static pressure was measured on each of the four sides of the house and averaged. The flow pressure $P_{total} - P_{static}$ was monitored in the bypass duct behind the bypass damper. The current drawn by the compressor and fan were individually monitored by placing a clamp-on ampmeter on each of their power cables. The voltage outputs of the ampmeters were calibrated against the power measured by a wattmeter during a one-time test. All sensor outputs were digitally scanned and averaged over 1-minute time intervals. Plots of all sensor responses were made over the duration of each mode. The plots demonstrate the zonal temperature and system cycling response to the thermostat setpoint.

The duration of the performance tests varied from mode to mode. Modes A, B, C and D were run overnight or for a few days at a time. A separate test, not listed in Table 2, was run over a few days to determine the temperature response of another configuration, but no data was taken to determine the system air flows or pressures during that test[1]. Some tests were run with an artificial separation barrier installed between zones 1, 2 and 4 and zone 3. To examine the effect of sealing return registers on system airflows in the artificial zones, performance tests for Modes E and F were run for periods of about 30 minutes. These tests were not run long enough to ensure adequate room temperature responses. In all cases the outside temperature was recorded as was the power supplied to the condenser and fan.

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[1] this test was performed by the Berkeley Solar Group

2.4 Data Analysis Procedures

2.4.1 Leakage Flowrates

Leakage flowrates were estimated for each duct leg by assuming a leakage flow characteristic of the type:

$$Q = K\Delta P^n$$

Values of K for each duct section were determined from leakage test data. The pressure difference used was the average of the supply plenum and supply register pressure minus the house interior pressure. The exponent in the leakage flow equation was assumed to be 0.65 based on previous studies in 31 houses (Modera, 1992).

The total airflow across the coil was determined by averaging the total supply side air flow and total return side air flow. The total supply side air flow is the sum of the air flow out the registers plus the supply leakage air flow. When the bypass damper was open, the bypass duct airflow rate was added to this sum. The return air flow is determined similarly. For modes E and F however, no pressure measurements were made in the economizer ducts, thus economizer leakage flows were not measured. For these modes, the total flowrate was slightly underestimated.

2.4.2 Sensible Energy Input

The total rate of sensible energy extracted from the cooling coil is:

$$\dot{E}_{\text{total}} = \dot{m}_{\text{coil}} C_p (T_{\text{SP}} - T_{\text{RP}})$$

here $\dot{m}_{\text{coil}}$ is the total mass flow rate of air across the coil while T_{SP} and T_{RP} are the supply and return plenum temperatures, respectively.

2.4.3 Duct Leakage Losses

Losses of sensible energy due to air leakage from the ducts were estimated for each supply zone by the equation:

$$\dot{E}_{\text{duct\_leak}} = \dot{m}_{\text{sup\_leak}} C_P (\overline{T_{\text{sup\_duct}}} - T_{\text{room}})$$

here $\dot{m}_{\text{sup\_leak}}$ is the leakage flowrate of air from the supply zone ducts, $\overline{T_{\text{sup\_duct}}}$ is the average temperature in the supply zone ducts and T_{room} is the room temperature.

The total leakage loss was the sum of all leakage losses over each supply duct:

$$\dot{E}_{\text{leak\_total}} = \sum_{\text{zones}} \dot{E}_{\text{duct\_leak}}$$

Return leakage losses were assumed negligible because the ducts were located inside the building envelope and because leakage of outside air through the return ducts was very low in comparison with the total flowrate.

The percent leakage loss was the ratio of the total leakage loss to the total sensible energy input:

$$L_{\text{leak}} = \frac{\dot{E}_{\text{leak\_total}}}{\dot{E}_{\text{total}}}$$

2.4.4 Duct Conduction Losses

Energy losses by conduction through the duct walls were estimated for each supply zone by the equation:

$$\dot{E}_{\text{duct\_cond}} = \dot{m}_{\text{reg}} C_p (T_{\text{SP}} - \overline{T_{\text{reg}}})$$

$\dot{m}_{\mathrm{reg}}$ is the sum of all air mass flow rates out the duct registers in each supply zone and $\overline{T_{\mathrm{reg}}}$ is the average of the zone register temperatures.

The total conduction energy loss was also the sum of the individual supply zone conduction losses:

$$\dot{E}_{\mathrm{cond\_total}} = \sum_{\mathrm{zones}} \dot{E}_{\mathrm{duct\_cond}}$$

The percent conduction loss was the ratio of the total leakage loss to the total sensible energy input:

$$L_{\mathrm{cond}} = \frac{\dot{E}_{\mathrm{cond\_total}}}{\dot{E}_{\mathrm{total}}}$$

Another method used in the literature to estimate duct conduction losses is to calculate the ratio of sensible heat loss from the air traveling down the duct to the sensible heat entering the duct. This indicates the fractional amount of entering energy that is lost by duct conduction:

$$L'_{\mathrm{cond}} = \frac{\dot{E}_{\mathrm{cond\_total}}}{\dot{E}_{\mathrm{duct\_in}}} = \frac{T_{\mathrm{SP}} - \overline{T_{\mathrm{reg}}}}{T_{\mathrm{SP}} - T_{\mathrm{RP}}}$$

where $\overline{T_{\mathrm{reg}}}$ is the average register temperature for all registers in the supply leg.

2.4.5 Duct Thermal Delivery Efficiency

Duct thermal efficiencies are the ratio of sensible energy leaving the duct system to the sensible energy entering it. Duct thermal efficiencies were computed for each leg of the supply ducts:

$$\eta_{\mathrm{th.}} = \frac{\dot{E}_{\mathrm{out}}}{\dot{E}_{\mathrm{in}}} = \frac{\sum_{\mathrm{zones}} \dot{m}_{\mathrm{reg}} C_p (\overline{T_{\mathrm{SR}}} - T_{\mathrm{room}})}{\dot{E}_{\mathrm{in}}}$$

where $\overline{T_{\mathrm{SR}}}$ is the averaged temperature over all registers in the supply zone. Duct thermal efficiencies indicate the combined energy losses of the ducts by leakage and conduction. The efficiencies are determined only for the ducts which service the conditioned zones, i.e. only for duct legs with open supply dampers.

Duct distribution efficiencies are the ratio of the total energy delivered to the conditioned space by the system with the ducts in place to that energy delivered without them. The duct distribution efficiency accounts for how much energy is ultimately delivered to the conditioned space. It can be written as:

$$\eta_{dist} = \frac{\dot{E}_{in} - \dot{E}_{to\_outside}}{\dot{E}_{in}}$$

where $\dot{E}_{to\_outside}$ is the sum of duct losses to outside the conditioned space.

3.0 Results

Leakage area results for the house envelope and air distribution system are presented first, followed by a summary of the pressures and air leakage rates measured for each mode of operation. System airflows and room temperature responses to thermostat setpoints under zone conditioning are presented next. A base case in which the house is conditioned as a single zone is first examined. This case is used to compare airflows and thermal response for the zone conditioning cases. A presentation of duct leakage and conduction losses, duct efficiencies and bypass damper impacts then follows.

3.1 Leakage Test Results

The effective leakage area (ELA) of the house envelope is shown in Table 3. Table 3 also lists the results of the leakage tests for the duct system. The envelope leakage area was measured twice, and the results differed by 7%. The average of the two envelope leakage areas was used to determine the specific leakage area (SLA) of the house. As shown, this house has an SLA of 2.5 cm^2 leakage area per m^2 of floor area. A study by Modera et.al. (1992) revealed SLA values of 4.5 cm^2/m^2 for 12 houses built in California after 1979. This house is tight by comparison with new construction in California.

Duct leakage areas were determined separately for each supply zone and the supply plenum. The results were summed together to determine the total supply side leakage. This result was compared to the result obtained by measuring the entire supply side leakage area, with all supply dampers open. This comparison showed very good agreement, with only 4 cm^2 difference between the two at 4 Pa (2%). The leakage areas at 25 Pa were included in Table 3 because they are more representative of the actual leakage area of the ducts during normal operation of the air distribution system. The flow exponent used in the 25 Pa column was 0.65.

TABLE 3. House envelope and duct leakage areas, pressurization

characteristic	ELA 4 Pa, cm^2	ELA 25 Pa, cm^2
Envelope:[a]		
test #1	678	-
test #2	727	-
Specific Leakage Area (cm^2/m^2)	2.5	-
Supply Ducts:		
zone 1	33	44
zone 2	32	41
zone 3	29	36
zone 4	48	62
supply plenum	48	64
total	190	247
measured total	186	245
supply → outside	28	36
Return Ducts:		
measured total	171	225
return → outside	32	43
Economizer:		
attic register	13	16
outside register	17	24
total	30	40
Total Supply and Return:	357	470
Specific Duct Leakage Area, (cm^2/m^2)	1.3	1.7

[a] envelope leakage only

In testing each supply zone for leakage, individual supply dampers were closed manually, but could not be observed, thus an unknown amount of leakage area around the supply damper may have been included in the total for that zone. However in the total supply side leakage test, the total leakage area was shown to be very close to the sum of the individual supply zone and plenum leakage areas. If there was significant leakage area around each supply damper, the sum of all individual zone leakage areas would exceed that of the total test by a significant amount. Because this is not the case, it was concluded that individual supply damper leakage area in each zone was negligible.

The return side showed leakage areas comparable to the supply side, a result which is typical of residential duct systems in general. Modera et.al. (1992) found that return side leakage areas in 31 houses averaged 13% higher than the supply side at 4 Pa. In this house, the total return leakage area was less than that on the supply side by about 10%. The house has a somewhat higher specific duct leakage area than has been found for typical houses in California, 1.3 vs. 1.0 cm^2/m^2 of floor area (Modera, 1992). However, the specific duct leakage area was significantly lower than that found in sheet metal ducts in 4 basement houses, which was 1.9 cm^2/m^2 (Treidler, 1993). Nevertheless, leak sealing efforts at the time of duct installation could have been improved with the aid of direct leakage measurement. Inspection of the accessible ductwork revealed leakage sites at duct connections to the supply plenum and along some of the sheet metal seams in the supply and return ducts. Duct connections at junctions may also have contributed to the overall supply leakage area, however this could not be confirmed due to the inaccessibility of most of the ductwork in the space between floors and in walls. Most of the duct leakage was not lost to outside, as most of the ducts were located inside the building envelope. The specific duct leakage area to outside at 4 Pa was 0.2 cm^2/m^2, which was 17% of the total. This is much lower than that found for typical California residences which have ducts in attics or crawlspaces where nearly all the leakage is to outside. The test house duct leakage to outside area is 80% lower in comparison. Leakage sites from the supply to outside were in the attic duct in supply zone 1, whereas on the return side sources of leakage were in the economizer ducts. In fact, tests on the economizer ducts in the attic and outside added up to very close to the total leakage area from the return side to outside.

3.2 Duct Performance

Table 4 shows the measured pressure differences in the ducts during system operation under each tested zone configuration. For each mode shown, the fan operated at low speed. Of particular interest was the increasing pressure in the distribution system with the closing of supply dampers. For cooling in all zones, 3 zones and 2 zones (i.e. Modes A, F and B respectively), the bypass damper remained closed and the resulting pressures increased significantly. The bypass damper opened only after 3 supply dampers closed. However pressures in the supply ducts remained high. The impact of high duct pressures on duct leakage will be shown.

Duct leakage rates during system operation are shown in Table 5. Supply leakage rates were highest for Mode B, even though two supply zones were closed. Return leakage was highest when the bypass damper was closed. When the return registers in the unconditioned zones were sealed in order to simulate return duct dampers (Mode E), the leakage rate increased. For each mode, supply duct leakage averaged approximately 16% of the total flow whereas the return leakage averaged roughly 25% of the total flow. Because the ducts were located inside the conditioned space, return leakage energy losses were much smaller than supply leakage losses due to the smaller temperature differences between duct interiors and surroundings. Supply duct air leakage represented a significant energy loss of the distribution system.

TABLE 4. Average static pressure differences between ducts and house interior under different configurations during system operation. "nm." indicates no measurement was taken. Units are Pa.

Location	Mode					
	A Cooling House as a Single Zone	B Cooling in 2 Zones (upstairs only)	C Cooling in 1 Zone (Mas. Bd.)	D Cooling in 1 Zone (w/ sep.)	E Cooling in 1 Zone (sep. & ret. damp.)	F Cooling in 3 Zones (sep. & ret. damp.)
zone 1	24	0	1	0	0	22
zone 2	21	0	0	0	0	23
zone 3	25	91	50	48	47	0
zone 4	22	81	1	0	0	21
supply plenum	40	136	75	69	70	37
return plenum	-68	-64	-31	-32	-55	-80
attic economizer	-40	-20	-9	-7	nm.	nm.
outside economizer	-51	-51	-29	-29	nm.	nm.
bypass duct (Pt -Ps)	0	0	21	30	34	0

TABLE 5. Leakage flowrate estimations, units are m^3/hr (cfm)

Location	Mode					
	A Cooling House as a Single Zone	B Cooling in 2 Zones (upstairs only)	C Cooling in 1 Zone (Mas. Bd.)	D Cooling in 1 Zone (w/ sep.)	E Cooling in 1 Zone (sep. & ret. damp.)	F Cooling in 3 Zones (sep. & ret. damp.)
zone 1	99 (58)	0	0	0	0	93 (55)
zone 2	85 (50)	0	0	0	0	92 (54)
zone 3	85 (50)	197 (116)	134 (79)	131 (77)	127 (75)	0
zone 4	134 (79)	311 (183)	0	0	0	129 (76)
supply plenum	200 (118)	445 (262)	304 (179)	285 (168)	289 (170)	190 (112)
return ducts + plenum	1001 (589)	965 (568)	601 (354)	607 (357)	872 (513)	1111 (654)
attic economizer	53 (31)	34 (20)	20 (12)	17 (10)	nm.	nm.
outside economizer	87 (51)	53 (31)	59 (35)	59 (35)	nm.	nm.
total fan flow	3345 (1969)	2773 (1632)	3284 (1933)	3456 (2034)	3534 (2080)	2989 (1758)

3.3 Zone Conditioning Results

3.3.1 Cooling the House as a Single Zone, Mode A

Supply and return register air flow rates, leakage rates and bypass duct air flow rates for single zone operation are shown in Table 6. The shaded areas in the table indicate which supply zone dampers were open, in this case all dampers were open. The bypass damper remained closed. Total supply air flow (i.e. register + leakage flow) for this configuration was 3583 m^3/hr (2109 cfm). The total return air flow was 3107 m^3/hr (1829 cfm), a difference of 15%. This difference stemmed from uncertainties in flow measurements and actual pressures across leaks. Table 6 also shows the percentage of air flow going to the conditioned zones (the sum of the shaded area flows) of the total supply flow (the sum of the total supply and supply leakage flow, excluding bypass duct flow). This is also shown for the return side. In the base case, 83% of the supply flow entering the ducts went to the supply zone, conversely 63% of the return air entered the ductwork at the return air registers.

TABLE 6. System Air Flows, Mode A, cooling in all zones.

Flow Type	Zone Flows m^3/hr (cfm)				Total		Conditioned Zones[a]
	1	2	3	4	cfm	%	%
supply register	1013 (596)	562 (331)	1070 (630)	336 (198)	2980 (1754)	83	83
supply leakage	99 (58)	85 (50)	85 (50)	134 (79)	603[b] (355)	17	-
return register	882 (519)	615 (362)	471 (277)	0	1967 (1158)	63	63
return leakage	-	-	-	-	1140 (671)[c]	37	-
bypass duct	-	-	-	-	0	0	-

[a] excludes bypass duct flow

[b] includes supply plenum leakage

[c] total return plus economizer leakage

Figure 1 shows the room temperature response to a cooling setpoint of 18.8 °C (66 °F) for each of the zones. The thermocouples were located in the main return register downstairs in the dining room and upstairs in the master bedroom return register. The room temperatures fluctuated approximately 1 °C during system cycling after an initial settling period. The average downstairs temperature was 18.4 °C during this period. Upstairs the average temperature was 19.6 °C. These temperatures agreed within 1 °C of the setpoint temperature, although the data indicated stratification of air temperatures in the house. The outside temperature is included in Figure 1 for comparison. Also shown on Figure 1 is the rescaled compressor power demand. This line shows when the system was on. During most of the testing period the compressor cycled on and off at low speed.

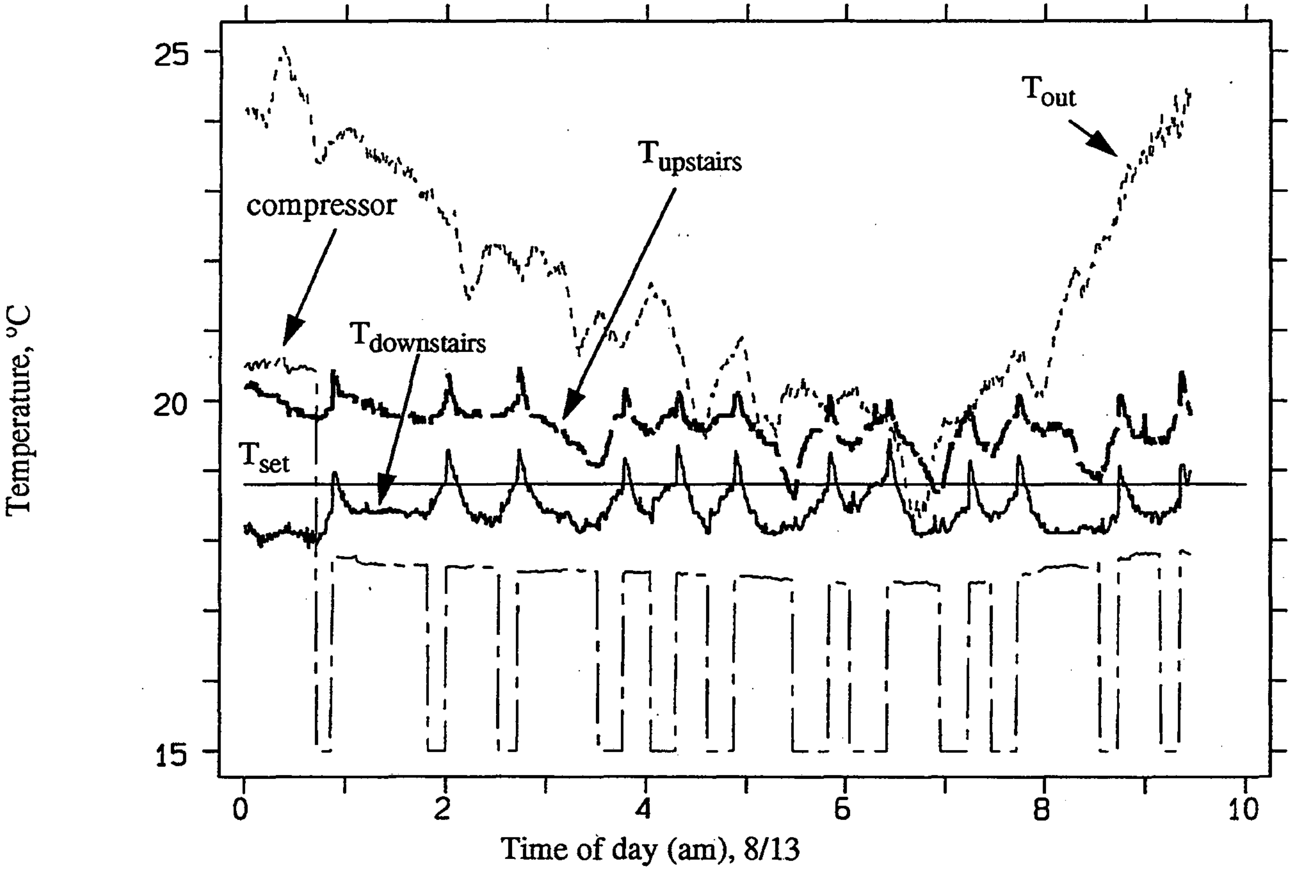

FIGURE 1. Cooling in all zones, room temperature response and outside temperature, °C, rescaled compressor power demand showing system operation. T_{set} = 18.8 °C, $\overline{T}_{up}$ = 19.6 °C, $\overline{T}_{down}$ = 18.4 °C

3.3.2 Upstairs Cooling Only, Mode B

TABLE 7. System Air Flows, Mode B, cooling in zones 3 and 4 only (upstairs).

Flow Type	Zone Flows m^3/hr (cfm)				Total		Conditioned Zones[a]
	1	2	3	4	cfm	%	%
supply register	161 (95)	127 (75)	1072 (631)	637 (375)	1998 (1176)	68	58
supply leakage	0	0	197 (116)	311 (183)	955[b] (562)	32	-
return register	736 (433)	304 (179)	501 (295)	0	1541 (907)	59	19
return leakage	-	-	-	-	1053[c] (620)	41	-
bypass duct	-	-	-	-	0	0	-

[a] excludes bypass duct flow

[b] includes supply plenum leakage

[c] total return plus economizer leakage

Table 7 shows the system air flows for the upstairs cooling only configuration, Mode B. For this case, the total supply flow dropped to 2953 m^3/hr (1738 cfm). On the return side the total was 2594 m^3/hr (1527 cfm), a difference of 12%. Of the air flow to the conditioned zones, a proportionally larger amount over that of the base case was lost to supply leakage. This was due to higher pressures driving up leakage rates in the supply ducts. Table 7 also indicates a significant amount of air flow in zones 1 and 2 resulting from dampers not completely closing during operation. On the return side there was a tremendous drop in the percentage of air flow coming from the conditioned zone, from 63 to 19%. This was not unexpected because the return ducts were open to the whole house, not just the conditioned zones. Return duct pressures and leakage rates did not change significantly from the base case.

The upstairs and downstairs setpoint temperatures for this configuration were 18.8 and 23.8 °C (66 and 75 °F), respectively. Figure 2 shows the upstairs and downstairs temperature response. In viewing the figure, the following observations can be made. The first is that both room temperatures varied approximately 2 °C during regular cycling of the air conditioner. It is interesting to note that when the air conditioner cycled off, the temperature in the main downstairs return register immediately dropped, indicating that cold air was back-circulating out of this return duct. The second and more important observation is that neither temperature cycled around its setpoint temperature. The average air temperature upstairs was 19.8 °C (after the initial cooling period) and downstairs it was 20.7 °C. Of the desired 5 °C temperature difference between zones, only 18% was realized.

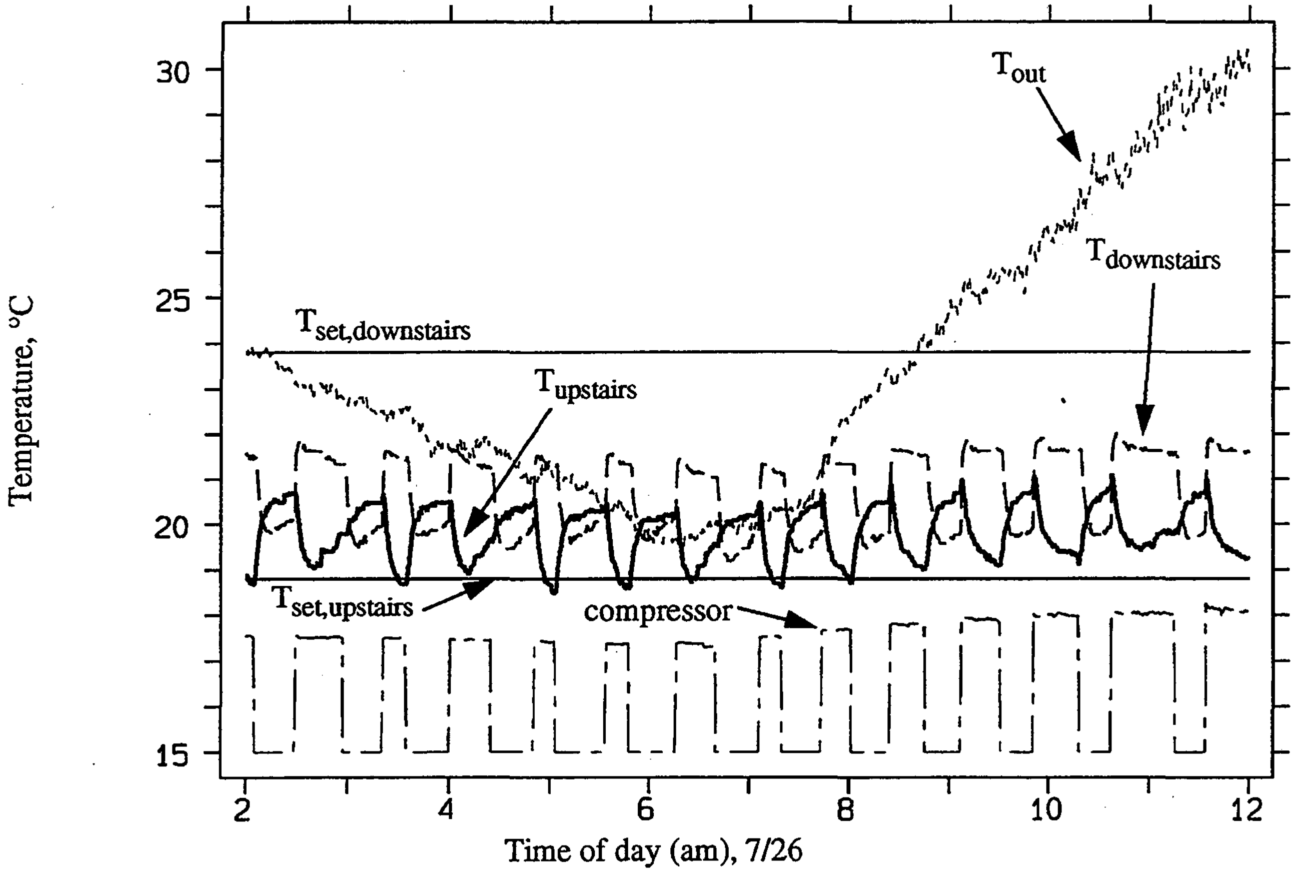

FIGURE 2. Upstairs cooling only, room temperature response and outside temperature, °C, rescaled compressor power demand showing system operation. $T_{set,up}$ =18.8 °C, $T_{set,down}$ = 23.8 °C T_{up} = 19.8 °C, T_{down} = 20.7 °C

3.3.3 Downstairs Cooling Only

Another test was run for cooling the downstairs zones only. No air flow data was collected for this test, however a thermostat setback schedule was included for each conditioned zone. In Table 8 the thermostat schedules are given. The schedules follow the CEC recommended setup schedules for zone conditioning (CEC, 1988). Figure 3 shows the zone temperature responses for this test. In the daytime, both upstairs and downstairs temperatures achieved their setpoint temperatures within approximately 1 °C. At night the downstairs temperature did not rise to its setup temperature due to the absence of heat loads. Between 9 am and 10 pm, the house achieved 70% of the desired temperature difference between upstairs and downstairs zones. In this configuration the zone temperature response performed well.

TABLE 8. Setback thermostat settings

Zone	Thermostat Setting	Time
Upstairs	25.6 °C	10pm to 9am
Upstairs	28.3 °C	9am to 10pm
Downstairs	25.6 °C	7am to midnight
Downstairs	28.3 °C	midnight to 7am

3.3.4 Master Bedroom Cooling Only, Mode C

TABLE 9. System Air Flows Mode C, cooling in zone 3 only, bypass duct open.

Flow Type	Zone Flows m^3/hr (cfm)				Total		Conditioned Zones[a]
	1	2	3	4	cfm	%	%
supply register	101 (59)	61 (36)	608 (358)	32 (19)	801 (471)	40	57
supply leakage	0	0	79 (46)	0	258[b] (152)	13	-
return register	246 (145)	128 (75)	195 (115)	0	569 (335)	30	20
return leakage	-	-	-	-	402[c] (237)	21	-
bypass duct	-	-	-	-	919 (541)	48	-

[a] excludes bypass duct flow

[b] includes supply plenum leakage

[c] total return plus economizer leakage

Isolating zone 3 for conditioning resulted in the system air flows of Table 9. Closing three supply zones caused the bypass damper to fully open, resulting in large air flows through the bypass

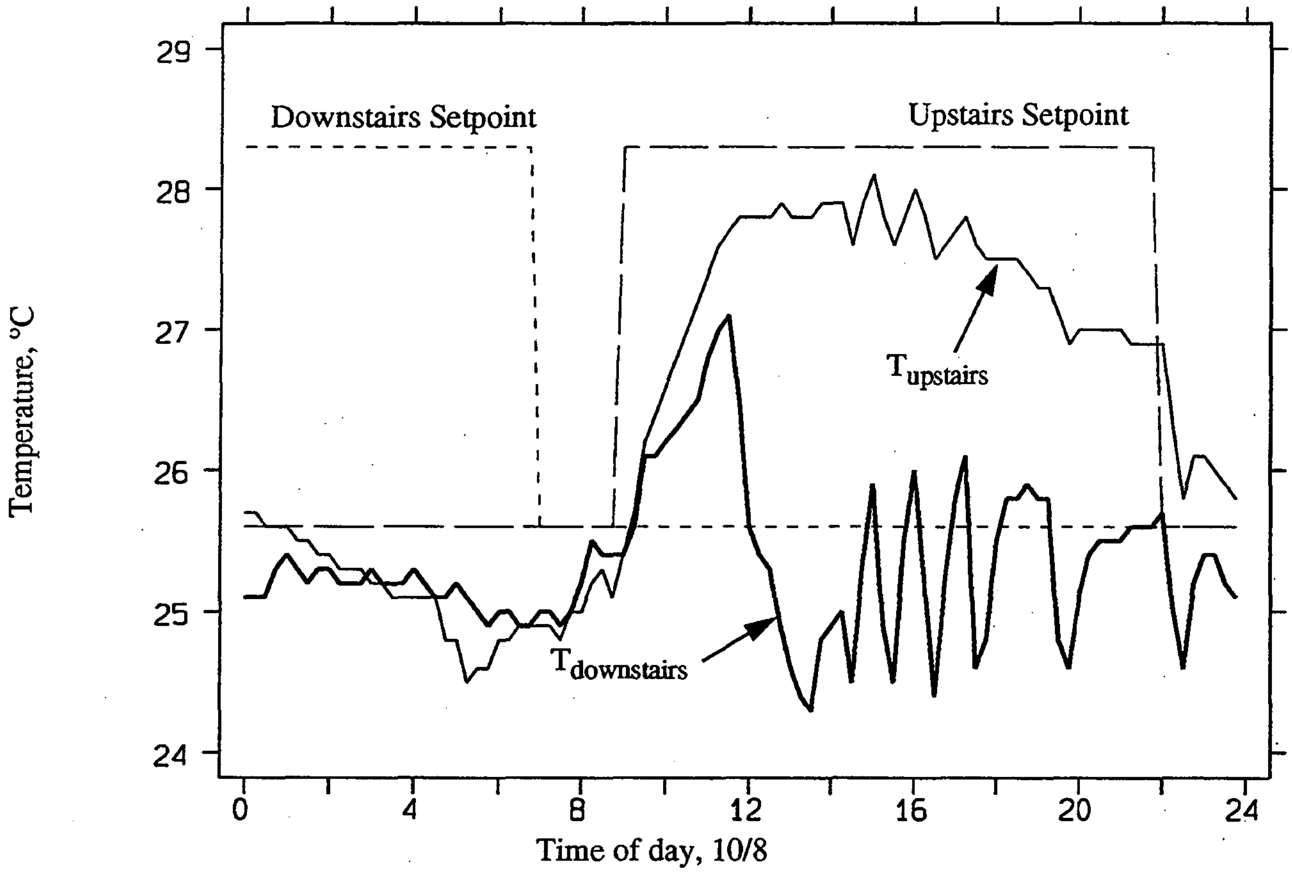

FIGURE 3. Downstairs cooling only, room temperature response, upstairs and downstairs thermostat schedules, average temperatures between 9 am and 10 pm: $\overline{T}_{up}$ = 27.4 °C, $\overline{T}_{down}$ = 25.5 °C

duct. Bypass duct airflow accounted for approximately 53% of the total flow through the air handler. On the supply side, the total air flow was 1799 m^3/hr (1059 cfm) (excluding bypass duct air flow), of which 57% was delivered to the conditioned zone. Once again, there was significant damper leakage flow in the other zones, as shown in the table. On the return side, the total flow was 1650 m^3/hr (971 cfm), 8% different from the supply side. The percentage of return air coming from the conditioned zone was very low, because all return registers were still open to the whole house.

The response to the master bedroom and downstairs setpoints is shown in Figure 4. For this case the compressor alternatively cycled to low and high speed during the beginning of the test period while both master bedroom and downstairs room temperatures were high. After achieving cooler temperatures in the house, the compressor cycled only at low speed, but remained on for longer time periods. Of the desired 5 °C temperature difference between zones, 32% was realized. The master bedroom achieved a temperature of only 21.1 °C, while the downstairs was 22.7 °C. Again, cool air in zone 3 mixed with air from the other zones through the open area between zones. A factor contributing to the mixing of air was that the total supply flow exceeded the total return flow in zone 3 by almost 680 m^3/hr (400 cfm), thus driving air out of zone 3.

3.3.5 Master Bedroom Cooling Only, With Zone Separation, Mode D

The same zone configuration as in Mode C was repeated with an artificial separation in place to halt the mixing of conditioned and unconditioned air between zones. Table 10 shows the resulting

TABLE 10. System Air Flows, Mode D, cooling in zone 3 only, with separation between living and sleeping zones, bypass duct open.

Flow Type	Zone Flows m^3/hr (cfm)				Total		Conditioned Zones[a]
	1	2	3	4	cfm	%	%
supply register	167 (98)	110 (65)	629 (370)	37 (22)	941 (554)	29	46
supply leakage	0	0	131 (77)	0	416[b] (245)	13	-
return register	335 (197)	199 (117)	615 (362)	0	1149 (676)	31	34
return leakage	-	-	-	-	683[c] (402)	18	-
bypass duct	-	-	-	-	1860 (1095)	54	-

[a] excludes bypass duct flow

[b] includes supply plenum leakage

[c] excludes economizer leakage

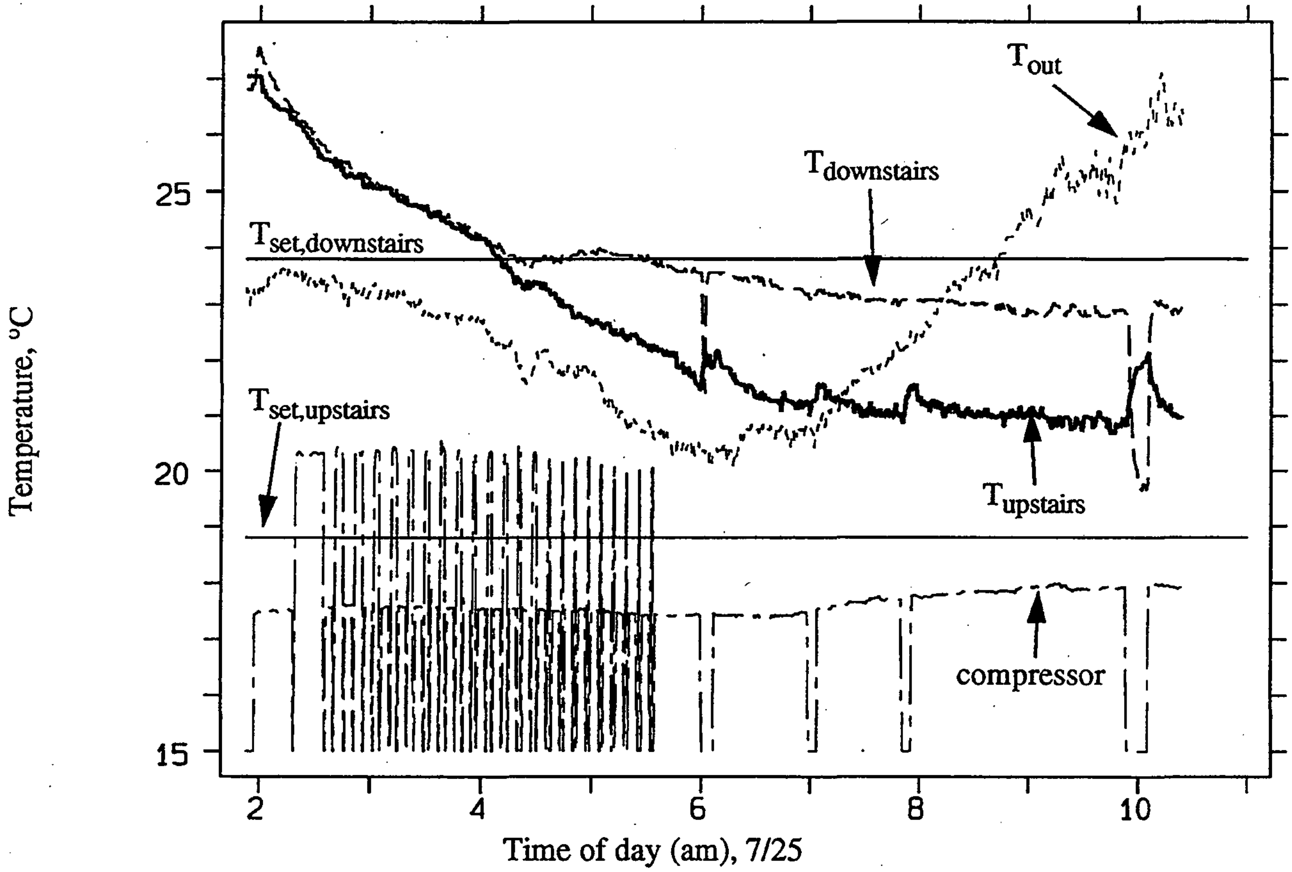

FIGURE 4. Master bedroom cooling only, room temperature response and outside temperature, °C, rescaled compressor power demand showing system operation. $T_{set,up}$ = 18.8 °C, $T_{set,down}$ = 23.8 °C, $\overline{T}_{up}$ = 21.1 °C, $\overline{T}_{down}$ = 22.7 °C

system air flowrates for this configuration. The bypass damper was fully open and accounted for 54% of the total air handler flow. Total supply flow into the supply ducts was 1358 m^3/hr (799 cfm). A lower fraction of the total supply flow was delivered to zone 3, 46% compared to 57% for the case with no zone separation. This was due to increased duct pressures and leakage. On the return side the total return airflow increased to 1832 m^3/hr (1078 cfm), of which 34% came from the conditioned zone. This was a 14% increase in return air flow over the configuration with no zone separation, a significant improvement. Damper leakage flow on the supply side was again high, which indicated a recurring problem of dampers not sealing properly when automatically closed by the control system.

Halting the flow of conditioned air out of zone 3 improved its thermal response to the setpoint temperature. Figure 5 shows that the agreement between the setpoint temperature (18.8 °C) and the zonal average temperature (19.7 °C) was much improved. The percentage of desired temperature difference between zones was also improved to 46%. The downstairs temperature maintained a reasonably constant value during the testing period. Interestingly the compressor on-time dropped significantly but the number of cycles per hour greatly increased, beyond that for single-zone cooling.

3.3.6 Master Bedroom Cooling Only, with artificial separation and simulated zone dampers, Mode E

Physically separating the conditioned from the unconditioned zones is one method of improving zoning performance, another is installing dampers in all return ducts. Return duct dampers were simulated for this house by sealing over the return registers in the unconditioned zones. The system airflows for this configuration are shown in Table 11. While the total supply flow remained low at 1555 m^3/hr (915 cfm), more of it was delivered to the conditioned zone, 58% of the total. On the return side, sealing the registers in the unconditioned zone increased the pressure (i.e. made it more negative) in the open return duct. The effect was to increase the amount of return air coming from the conditioned zone to 44%, which was a favorable impact. An unfavorable impact was the increase of return leakage due to the increase in pressure. The total return flow was 1551 m^3/hr (913 cfm), negligibly different from the supply flow.

3.3.7 Cooling in Living Zone only, with separation and simulated return duct dampers, Mode F

The final zone configuration studied was the reverse of the previous case, that is, the living zone was conditioned, with artificial separation in place between zones and with the returns in zone 3 sealed. The system flows are shown in Table 12. For this case the bypass damper was closed. The total supply

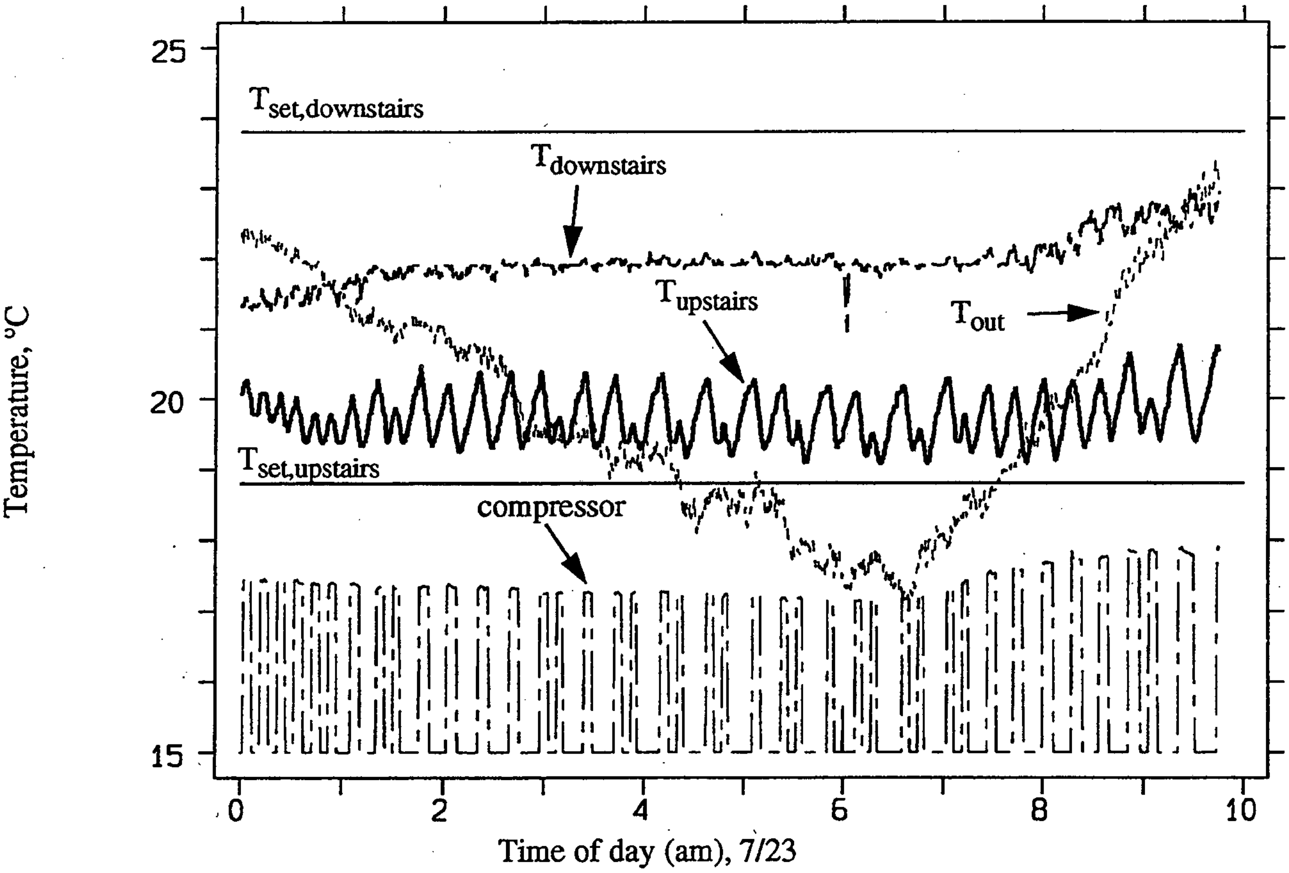

FIGURE 5. Master bedroom cooling with installed zone separation, room temperature response and outside temperature, °C, rescaled compressor power demand showing system operation. $T_{set,up}$ = 18.8 °C, $T_{set,down}$ = 23.8 °C, $\overline{T}_{up}$ = 19.7 °C, $\overline{T}_{down}$ = 22.0 °C

TABLE 11. System Air Flows, Mode E, cooling in sleeping zone, with separation between living and sleeping zones, return registers in living zone sealed, bypass duct open.

Flow Type	Zone Flows m^3/hr (cfm)				Total		Conditioned Zones[a]
	1	2	3	4	cfm	%	%
supply register	175 (103)	41 (24)	897 (528)	20 (12)	1133 (667)	32	58
supply leakage	0	0	127 (75)	0	418[b] (246)	12	-
return register	0	0	683 (402)	0	683 (402)	19	44
return leakage	-	-	-	-	872[c] (513)	25	-
bypass duct	-	-	-	-	1981 (1166)	56	-

[a]excludes bypass duct flow

[b]includes supply plenum leakage

[c]excludes economizer leakage

flow was 3124 m^3/hr (1839 cfm) and for the return it was 2848 m^3/hr (1676 cfm), a difference of 8%. The fraction of air delivered to and returned from the conditioned zone was comparable to the base case. Supply and return leakage rates were also similar in magnitude to the base case. The actual return leakage rates are expected to be slightly larger than the tabulated values for both modes E and F, due to the absence of economizer duct leakage rate estimations. There were no air distribution system performance tests run for both modes E and F.

TABLE 12. System Air Flows, Mode F, cooling in living zone, with separation between living and sleeping zones, return registers in sleeping zone sealed, bypass duct closed.

Flow Type	Zone Flows m^3/hr (cfm)				Total		Conditioned Zones[a]
	1	2	3	4	cfm	%	%
supply register	951 (560)	1074 (632)	224 (132)	370 (218)	2620 (1542)	84	77
supply leakage	93 (55)	90 (53)	0	129 (76)	505[b] (297)	16	-
return register	1201 (707)	535 (315)	0	0	1736 (1022)	61	61
return leakage	-	-	-	-	1111[c] (654)	39	-
bypass duct	-	-	-	-	0	0	-

[a]excludes bypass duct flow

[b]includes supply plenum leakage

[c]excludes economizer leakage

3.4 Duct Leakage Losses

The previous sections showed the fraction of air flow that was lost through duct leakage and the resulting temperature response of the zones. The fraction of sensible energy lost by supply duct leakage of the total sensible energy into the air distribution system is shown in Table 13. The total sensible energy input to the distribution system excludes the sensible energy recirculated back to the return plenum through the bypass duct when it is open. Modes D, E and F are not shown because supply register temperatures did not achieve steady state values. Leakage losses were lowest when conditioning in all zones, Mode A. For cooling in one or two zones only, the leakage losses were higher because of the higher driving pressures in the ducts due to the closing of supply dampers. The highest supply leakage losses were found for the case with the highest duct pressures, Mode B. For Mode C, duct pressures were lower than in Mode B because the bypass damper was open. In each case, the leakage losses from the supply plenum was highest.

TABLE 13. Duct Leakage Losses of Sensible Energy Input

Mode	Duct Leakage Loss (%of sensible energy input)					
	zone 1	zone 2	zone 3	zone 4	sup. pl.	total
A	2.5	2.2	2.1	3.5	5.8	16
B	0	0	5.9	10	14.1	30
C	0	0	6.4	0	15.6	22

3.5 Duct Conduction Losses

TABLE 14. Duct Conduction Losses, Fraction of Sensible Energy Entering Ducts

Mode	Duct Conduction Loss, %			
	zone 1	zone 2	zone 3	zone 4
A	19	17	25	18
B			13	3
C			26	
26 House Study (Modera, 1992)				23

Another source of energy loss in the ducts resulted from heat conduction through the duct walls. Table 14 shows the percentage of energy lost through the duct walls as a fraction of the energy entering the duct section. It should be noted that this approximated the conduction loss if there was no leakage and therefore cannot be simply added to the leakage loss.

For cooling in all zones, the conduction loss from the air traveling through the ducts averaged 20% over all supply ducts. This was comparable to the 23% conduction losses determined for 26

California houses (Modera et. al., 1992). However in that study all ducts were located primarily in attics and crawlspaces and were minimally insulated to R3 or R4. It would be expected that moving the ducts inside the conditioned space would provide a substantial reduction in conduction losses due to the lower temperatures around the ducts. Because the duct runs were long and uninsulated and made of sheet metal, the actual reduction was not as great as expected. It should be noted that the conduction energy loss in this house was not lost to the house exterior, as it was in the cited study. Instead the loss was in terms of response to thermostat setpoints, as not all of the cool air was delivered to the zone as intended. This was not significant when the entire house was cooled as a single zone, or when cooling was required in the downstairs zones only. For configurations where cooling was required in one or both of the upstairs zones, the losses were significant as they were not recovered by natural buoyant forces.

The conduction losses for Mode B, upstairs cooling only, deserve mentioning because of their low values in comparison with those of the other modes. In this configuration the bypass damper was closed while only two supply zone dampers were open and the fan was running at low speed. As Table 4 showed, the duct pressures were the highest measured for any mode. This meant also that air velocities in the ducts were the highest, cutting significantly the residence time in the ducts (i.e. the time that the air was in actual contact with the duct walls). Thus conduction losses for this configuration were lower simply because the air mass spent less time in contact with the duct walls.

TABLE 15. Duct Conduction Losses, Fraction of Total Sensible Supply Energy

Mode	Duct Conduction Loss, %				
	zone 1	zone 2	zone 3	zone 4	total
A	5.6	5.3	4.2	1.8	17
B			4.7	.2	5
C			8.2		8

The fraction of energy lost by supply duct conduction of the total energy into the air distribution system is shown in Table 15. Conduction losses from the supply plenum were not determined. The highest conduction losses occur for the single zone cooling mode, where residence times of air in the ducts were longest. In comparison with leakage losses, conduction losses were of the same magnitude only for Mode A.

3.6 Duct Efficiency

Two ways of characterizing distribution system performance may be used. The first is the thermal delivery efficiency, which indicates the fraction of cooling energy which is delivered at the registers. The thermal delivery efficiencies of the air distribution system for the three cases are given in Table 16. Delivery efficiencies account for all supply and return leakage and conduction losses in the system. Supply duct leakage and conduction losses were given in the previous sections. Return leakage and conduction losses were not calculated, but were expected to be small because of the small temperature differences between the ducts and surroundings due to their placement inside the building envelope. When the house was configured for cooling in all zones, the delivery efficiency was highest, 64%. In comparison, average annual delivery efficiencies of 67% were reported in a simulation study by Jansky (1993) for attic ducts in Sacramento houses.

TABLE 16. Duct Thermal Delivery Efficiencies

Mode	T_{out} °C	$\eta_{th.}$%
A	23.8	64
B	36.7	49
C	24.0	48

When conditioning the house in two zones or in one zone only, the thermal delivery efficiencies dropped by 15%. Different effects accounted for the dropoff in the efficiencies for these modes. In Mode B, supply duct conduction losses have been shown to be the lowest, because of high pressures causing short residence times of air in the ducts. However, the same high pressures caused significant energy loss by duct leakage. As Table 13 showed, the leakage loss increased 14% for Mode B. For Mode C, duct pressures have been reduced somewhat by the opening of the bypass damper. While there remained predominant losses due to duct leakage, conduction losses once again increased due to the colder supply plenum temperatures and longer residence times.

TABLE 17. Energy Accounting by Mode

Mode	$\eta_{th.}$%	Supply Leakage Losses, %	Supply Conduction Losses, %	Sum, % Energy into ducts
A	64	16	17	97
B	49	30	5	84
C	48	22	8	78

Table 17 shows the sum of the duct thermal delivery efficiency and the percentage of supply leakage and conduction losses. The sum should add up to nearly 100%. This is the case for Mode A, but not for Modes B and C. Both of these modes were operated under a zoning configuration, and in Mode C, the bypass damper was open.

When zoning there was a large volume of return air from unconditioned zones, due to the absence of return duct dampers. While the temperature difference was small, approximately 80% of the return airflow was coming from unconditioned zones, as shown in Tables 7 and 9. This represented an additional loss of approximately 10% for Mode B and 5% for Mode C. The balance of losses for Mode C are leakage and conduction losses in the bypass duct, because of the large flow of air at lower temperatures when the damper is open.

The thermal delivery efficiency is a good indicator of the duct system's ability to zone. Specifically, low thermal delivery efficiency hampers zoning performance. When conditioning in the upstairs zones, the thermal delivery efficiency was reduced to 50%. For these cases 18% of the desired temperature difference between zones was realized.

Unlike attic ducts, sensible energy losses from the air distribution system in the test house were not lost to the house exterior. The thermal delivery efficiency may thus be a somewhat misleading indicator of the distribution system performance for cooling the house as a single zone. The second way to characterize duct system performance is with the distribution efficiency. The distribution efficiency is defined by the ratio of the total energy delivered to the conditioned space by the system with the ducts in place to that energy delivered without them. This number indicates how much of the conditioned air ultimately reaches the conditioned space. For cooling the house as a single zone, losses to outside were primarily leakage through the economizer registers in the attic and outside and conduction losses from the short duct run over the breakfast nook. The distribution efficiency was approximately 98%. This is much higher than distribution efficiencies in attic or crawlspace duct houses, which are approximately equal to delivery efficiencies. The distribution efficiency has a high value as a result of placing practically all the ducts inside the building envelope.

3.7 Bypass Damper Impacts

The impact of bypass duct air flow on equipment and air distribution system efficiencies was high. In our tests, the bypass damper opened when cooling in one zone only. Opening the bypass damper served to maintain high air flowrates across the coil, as Table 18 shows.

TABLE 18. Bypass Damper Impacts

Mode	Bypass Damper Position	Flowrate across coil m^3/hr (cfm)	T_{SP} °C	T_{RP} °C
A	closed	3345 (1969)	10	19.5
B	closed	2773 (1632)	13.2	21.5
C	open	3286 (1934)	9.0	16.7
D	open	3456 (2034)	8.0	13.6
E	open	3534 (2080)	8.3	14.4
F	closed	2987 (1758)	13.4	22.5

The added effect of recirculating supply air back to the return plenum was to decrease both the supply and return plenum temperatures and reduce the temperature difference across the coil. In the absence of condensation at the coil, reducing the temperature difference decreased the cooling capacity of the air conditioner. Thus when cooling in one zone only the bypass damper effectively adjusted the cooling capacity by reducing the system efficiency. Delivering colder supply air also served to increase existing leakage and conduction losses to the upstairs zones in the air distribution system.

4.0 Discussion

In assessing the zoning performance in the test house, a number of issues must be addressed. These issues fall primarily into two categories: house design and air distribution system design. House design issues include placing the air distribution system inside the conditioned space, the separation of individual house zones and the large internal volume of the house. Air distribution design issues include duct material, absence of return duct dampers and impacts of the bypass duct. These issues are addressed here.

Installing uninsulated spiral sheet metal ducts in the house did not reduce the total duct conduction losses (20%) significantly in comparison to that for houses with attic ducts (23%). The specific duct leakage area (1.3 cm^2/m^2) was more than that for typical California construction (1.0 cm^2/m^2) indicating that leak sealing efforts at the time of construction would have benefitted from direct leakage measurements. Combined leakage and conduction losses reduced the duct delivery efficiency to 64% when cooling in all zones, which is comparable to that for houses with attic duct installations. When cooling the upstairs zones the duct delivery efficiency was reduced to 50%.

Placing the ducts inside the conditioned space reduced the duct losses to outside almost to zero. This was important because total duct leakage and conduction losses were not significantly lower than that for typical California construction. In duct leakage tests, the fractional amount of estimated duct leakage area to outside was 17% of the total leakage area and about 80% less than that found in attic duct installations. Conduction losses outside the conditioned space were small because of the minor duct outside surface area. Locating the ducts inside improved the distribution efficiency to 98%, which is approximately 20% greater than the norm.

The house layout prevented ideal separation of the four different zones without a large open area between them. Supply zone registers were common to the same space for zones 1, 2 and 4 and it was impossible to separate them by simply closing internal doors. Zone 3 could be separated from the other zones by an open area less than the CEC limit, but only if a supply register in bathroom 1 was sealed. Two return registers could be assigned to zone 3 with our modifications, however they were undersized in that supply airflow in zone 3 always exceeded return flow by at least 170 m^3/hr (100 cfm) for all modes tested.

The major impact on the zoning performance was thermal stratification in the house. The open floor plan and large internal volume of the house enabled significant temperature differences to be set up between upstairs and downstairs rooms. When all thermostats were given the same setpoint, a 1.2 °C (2 °F) difference between stories was obtained. Ignoring for the moment all other factors influencing zoning performance, thermal stratification played a positive role when cooling was called for in the downstairs zones and worked against the air distribution system when cooling in the upstairs zones. Air was allowed to mix and stratify because of the large open area between zones. The undersizing of the return ducts in zone 3 also encouraged air mixing between zones. When factoring in the impact of duct losses, downstairs zoning performance improved while upstairs zoning performance diminished. This was due to the communication with duct leakage and conduction losses through the vented access panels in the dining room ceiling. The difference between upstairs and downstairs zoning performance was evidenced by the system achieving only 18% of the desired temperature difference when cooling in the upstairs zones and 70% of the desired difference when cooling the downstairs only.

The lack of installed return duct dampers allowed severe mixing of return air from unconditioned zones. When zoning, typically only 20% of the total return air came from the conditioned zone, the remaining air coming from unconditioned zones and return air leakage. This increased the cooling load unnecessarily and may have eliminated any gains made from zoning.

The reduction in supply and return plenum air temperature when the bypass damper was open reduced the amount of sensible heat transfer from the coil. As a result, the air conditioner efficiency was negatively affected when zoning. When zoning, some form of capacity modulation is required in order to realize energy savings. While the open bypass duct reduces the amount of delivered energy to the conditioned zone, it does not simultaneously reduce the compressor power demand. Its purpose was to maintain the airflow across the coil. When open, the bypass duct was another source for leakage and conduction energy losses, because the temperature difference between the air flowing through the duct and its surroundings was large in comparison with other ducts.

5.0 Conclusion and Recommendations

This report identified a number of issues that both positively and adversely affected zoning performance of the house and air distribution system. These issues were: advantages of placing the ducts inside the conditioned space, the impact of distribution system losses on zoning performance, the effects of thermal stratification, the absence of return duct dampers and the impact of the bypass duct.

Installing uninsulated spiral sheet metal ducts did not reduce the amount of conduction losses through the duct walls as compared to attic and crawlspace conduction losses in houses with standard duct insulation in California, in fact the percent losses were nearly the same in both cases. Duct leakage area in the test house was poorer than that found in the typical California house, but better than that found for other houses with sheet metal ducts. These factors served to negate any gains in duct delivery efficiency realized from placing the ducts in the conditioned space. However the leakage and conduction losses to the outside were dramatically reduced. While the duct delivery efficiency was affected by these losses, placing the ducts inside the building envelope improved the distribution efficiency markedly in comparison with that of houses with attic or crawlspace ducts for the simple reason that duct losses inside the test house were recovered.

Optimal zoning performance was hindered primarily by thermal air stratification. Another factor was the lack of return duct dampers, which allowed mixing of up to 80% of air from unconditioned zones. Interzonal air mixing was also a problem, because of the large open areas between zones. Thermal air stratification in the house played dual roles, aiding the zoning performance when the house was cooled in all zones or in the downstairs zones only, while worsening the performance for upstairs cooling strategies. While the lack of return duct dampers and the duct leakage and conduction losses reduced the system's capability to zone, the large open areas between zones and thermal air stratification were the most important determinants of zoning performance.

Two other conclusions can be drawn from this work. Adding a dampered bypass duct to the air distribution system to maintain the air flow rate across the coil does not seem to be a good form of capacity modulation. Its overall effect is to reduce the equipment cooling efficiency by reducing its capacity when the bypass damper is open. Concerning leak sealing, even the best intentions to find and seal leaks in the air distribution system can be improved by measurement. Utilizing one of the known leak sealing techniques during the house construction is recommended.

Finally, utility programs or building standards promoting zoning as a means of conserving energy or reducing peak power demand should be aware of the many potential pitfalls that could arise with zone conditioning, particularly with dampered air distribution systems. The whole house and all its interactions with the air distribution system must be considered in the design phase.

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Appendix A

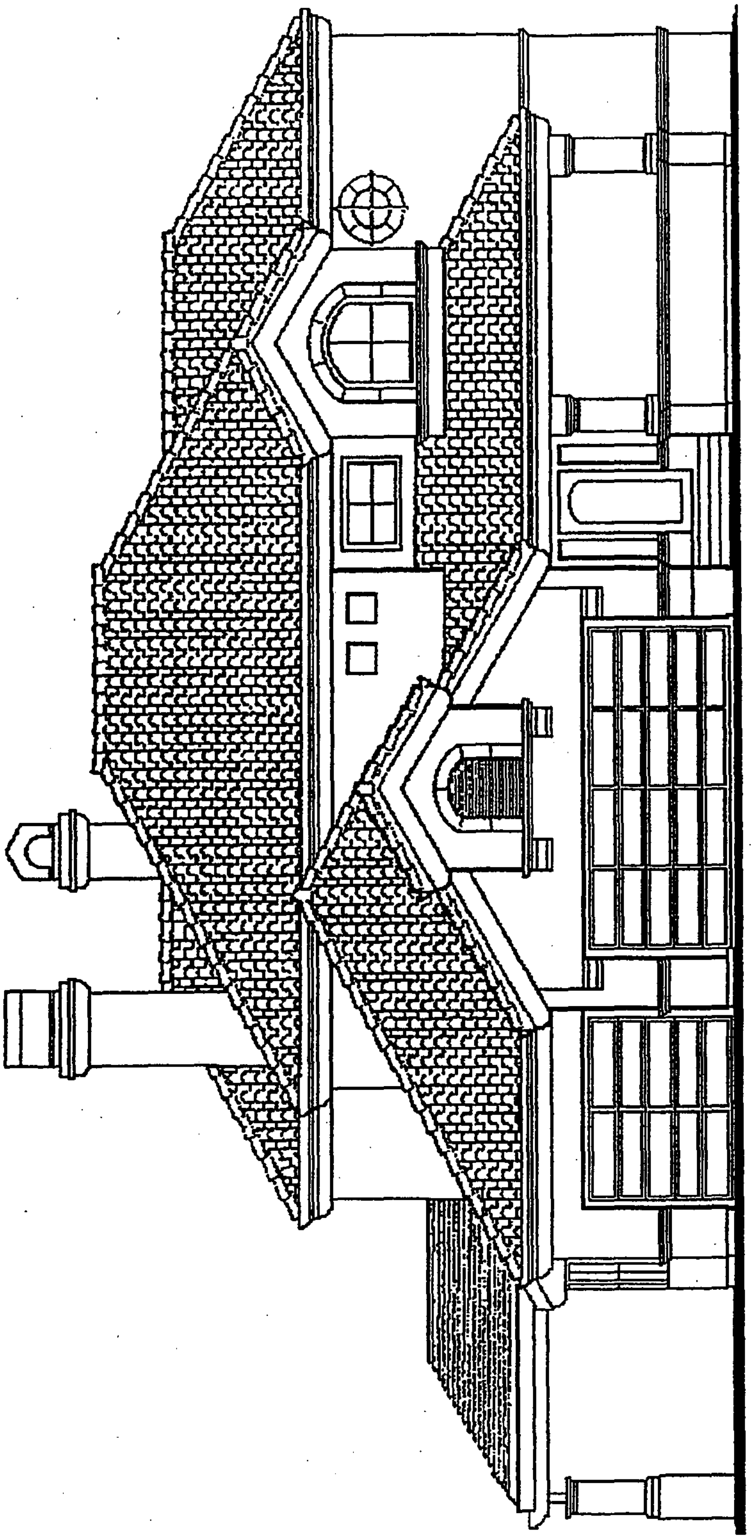

Figure A1. Front View of Test House

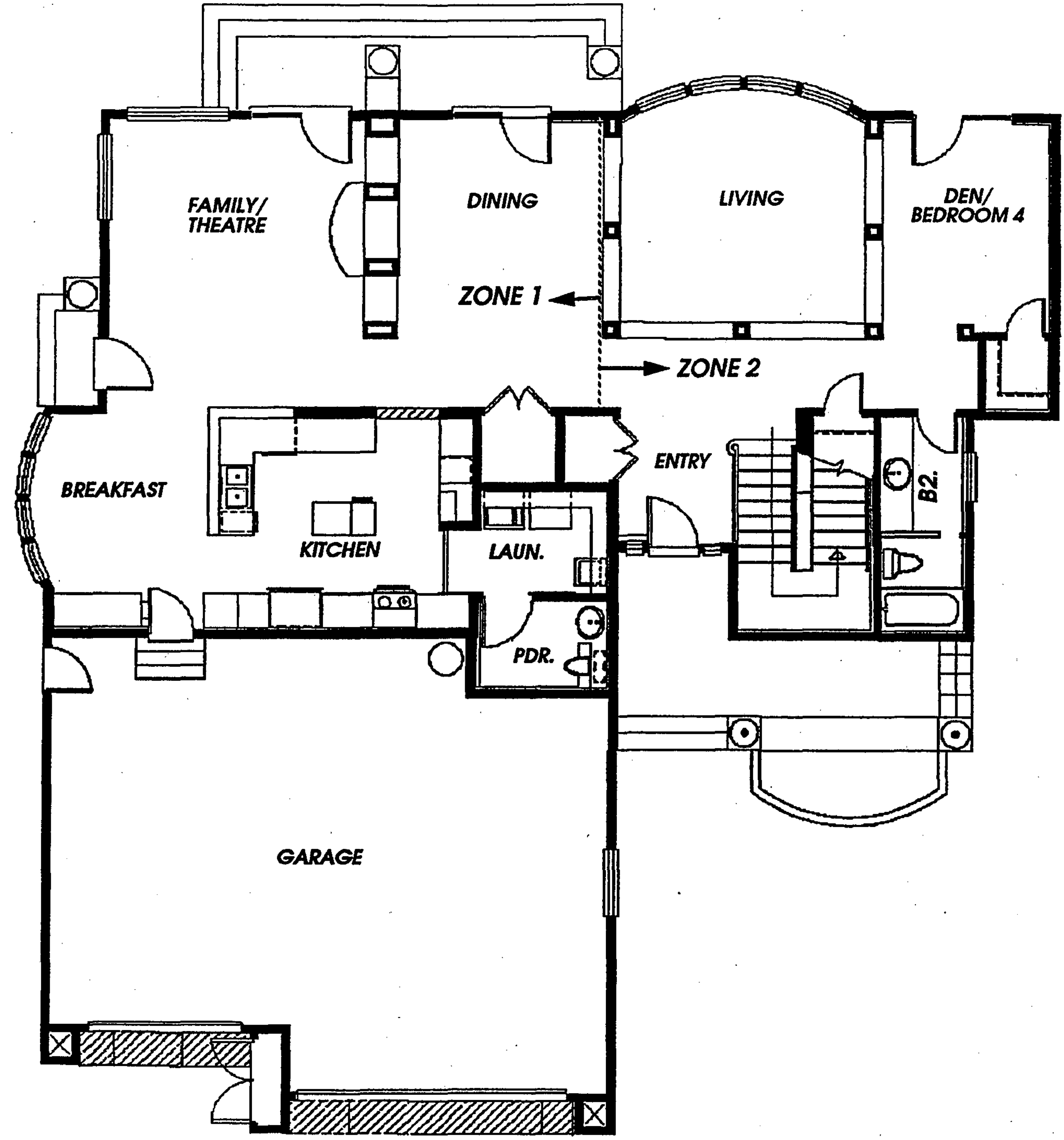

Figure A2. Test house downstairs floor plan (not to scale).

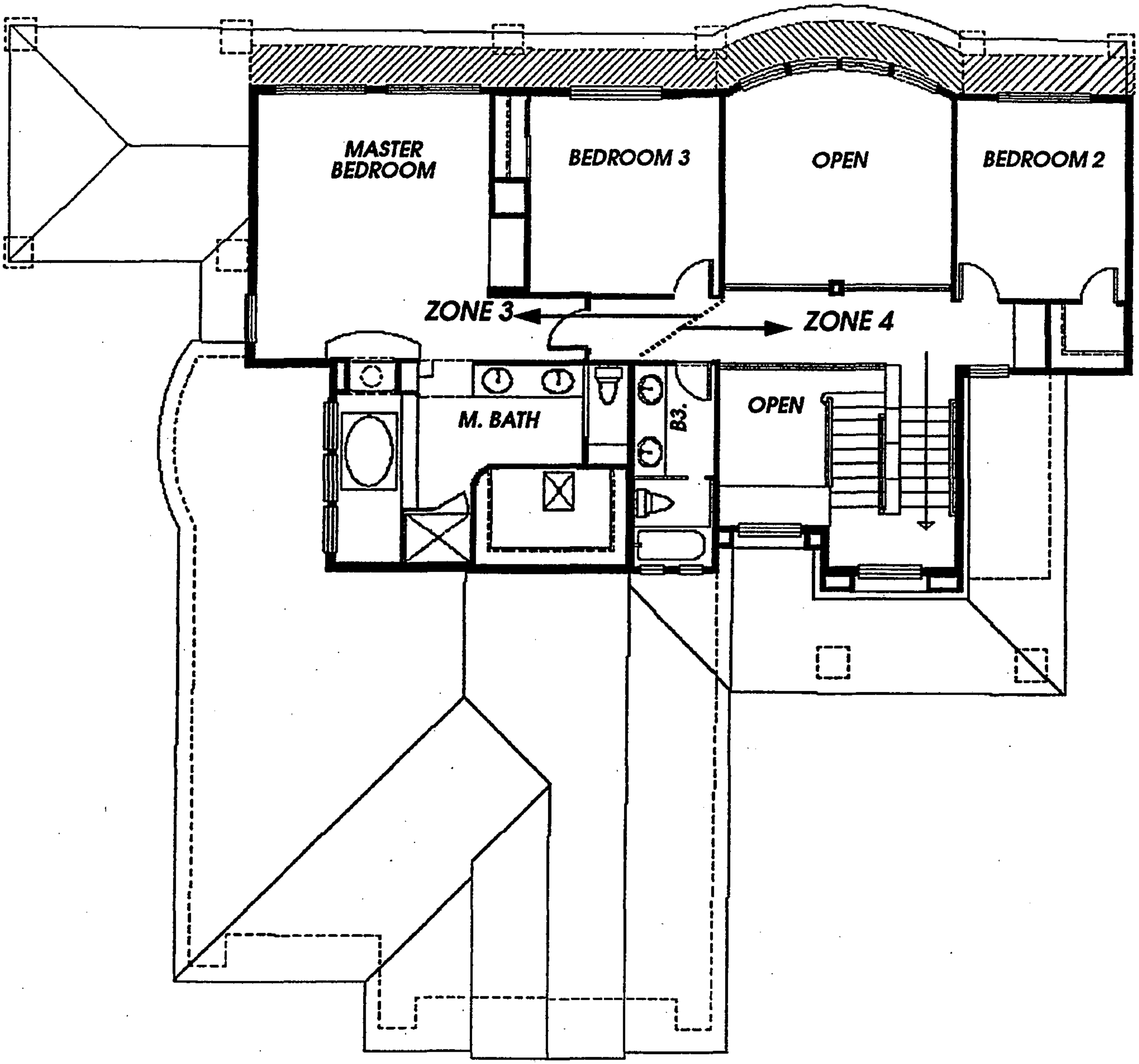

Figure A3. Test house upstairs floor plan (not to scale).

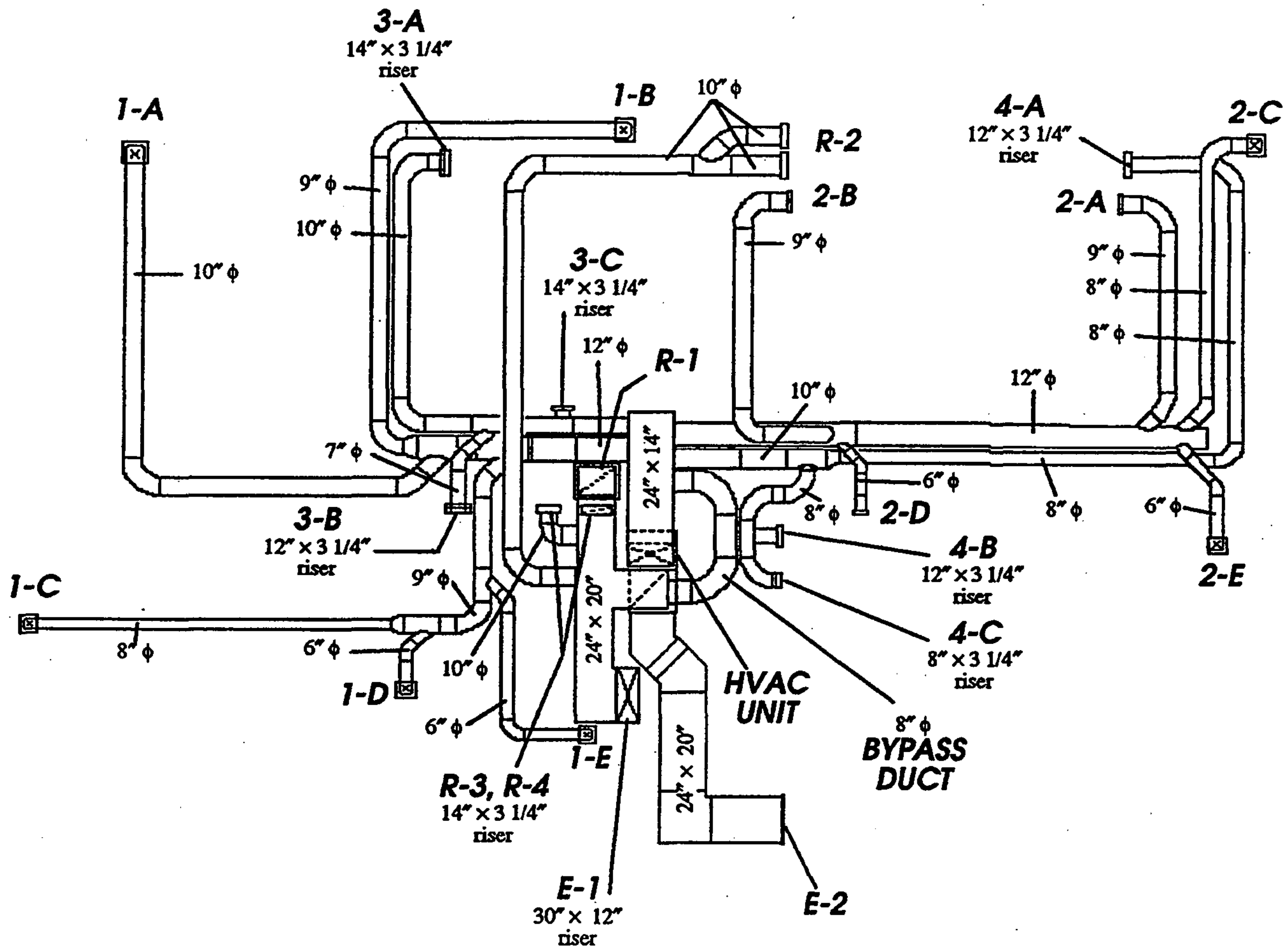

Figure A4. Duct system layout, location is between floors (not to scale). Register dimensions in accompanying table.

Table A1. Register locations and dimensions

Zone	Register		Room	Dimensions
	Name	Type		
1	1-A	ceiling	Family Room	12″ × 12″
	1-B	ceiling	Dining Room	10″ × 10″
	1-C	ceiling	Breakfast Nook	10″ × 10″
	1-D	ceiling	Kitchen	6″ × 6″
	1-E	ceiling	Laundry Room	6″ × 6″
2	2-A	wall	Living Room East	12″ × 6″
	2-B	wall	Living Room West	12″ × 6″
	2-C	ceiling	Bedroom 4	10″ × 10″
	2-D	wall	Hall Entryway	6″ × 4″
	2-E	ceiling	Bathroom 2	6″ × 6″
3	3-A	wall	Master Bedroom	14″ × 8″
	3-B	wall	Master Bathroom	12″ × 4″
	3-C	wall	Bedroom 3	14″ × 8″
4	4-A	wall	Bedroom 2	14″ × 8″
	4-B	wall	Top of Entryway	12″ × 6″
	4-C	wall	Bathroom 3	8″ × 4″
returns	R-1	ceiling	Dining Room	24″ × 20″
	R-2	wall	Top of Living Room	30″ × 12″
	R-3	wall	Master Bedroom	14″ × 8″
	R-4	wall	Upstairs Hall	14″ × 8″
economizer	E-1	attic	Attic	30″ × 12″
	E-2	outside wall	Oustside - Front Door	36″ × 36″

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