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Improving the Energy Efficiency of Residential Air-Distribution Systems in California

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PHASE I

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IMPROVING THE EFFICIENCY OF RESIDENTIAL AIR-DISTRIBUTION SYSTEMS IN CALIFORNIA

Phase I

Prepared for the

California Institute for Energy Efficiency

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SUMMARY

This report describes the results of the first phase of a multiyear research project. The project's goal is to investigate ways to improve the efficiency of air-distribution systems in detached, single-family residences in California. First-year efforts included:

- A survey of heating, ventilating, and air conditioning (HVAC) contractors in California.
- A 31-house field study of distribution-system performance based on diagnostic measurements.
- Development of an integrated air-flow and thermal-simulation tool for investigating residential air-distribution system performance.

The major findings of the contractor survey are presented here, as are the results of the field study and the first applications of the simulation tool. The field-study results generally agree with the findings of earlier, more limited studies. The study provided both field confirmation of improved diagnostic tools and additional system/house characterization data. That data will be used to input and verify simulation codes and develop retrofit protocols. Highlights of the field results include the following:

- Building envelopes for houses built after 1979 appear to be approximately 30% tighter.
- Duct-system tightness showed no apparent improvement in post-1979 houses.
- Distribution-fan operation added an average of 0.45 air changes per hour (ACH) to the average measured rate of 0.24 ACH.

The simulation tool developed is based on DOE-2 for the thermal simulations and on MOVECOMP, an air-flow network simulation model, for the duct/house leakage and flow interactions. The first complete set of simulations performed (for a ranch house in Sacramento) indicated that the overall heating-season efficiency of the duct systems was approximately 65% to 70% and that the overall cooling-season efficiency was between 60% and 75%. The wide range in cooling-season efficiency reflects the difference between systems with attic return ducts and those with crawl-space return ducts, the former being less efficient.

The simulations also indicated that the building envelope's UA-value, a measurement of thermoconductivity, did not have a significant impact on the overall efficiency of the air-distribution system.

INTRODUCTION

BACKGROUND

Approximately 50% of the households in the U.S. have central warm-air furnaces and air-distribution ducts (DOE 1987). That translates into approximately 1 million miles of residential ducts. Because of their widespread use and their role as the vital link between houses and their space-conditioning plants, residential duct systems' energy-effectiveness and comfort are regularly revisited as topics of study. Interested parties, including the Gas Research Institute (Orlando and Gamze 1980), researchers at the National Bureau of Standards and Princeton University (Grot and Harrje 1981) and at Brookhaven National Laboratory (BNL 1986), and a special project committee of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) (Jacob et al. 1986a; Jacob et al. 1986b; Locklin et al. 1987), have all reached the same conclusion: Air-distribution systems can have significant impacts on residential heating and cooling.

A number of studies have also measured significant changes in building air-infiltration rates due to air-distribution system operation. Researchers at Oak Ridge National Laboratory (ORNL) measured an average increase of 80% in the infiltration rate of 31 Tennessee houses whenever their distribution fans were operated (Gammage et al. 1986). In more detailed testing involving five houses, researchers in Florida noted that the infiltration rate tripled when the distribution system was operated with internal doors open; that rate was further tripled when the doors between rooms were closed during system operation (Cummings and Tooley 1989). Both the infiltration-rate increases in the Tennessee houses and the initial tripling of the air-change rate of the Florida houses were attributed to leaks in the ducts passing through unconditioned spaces, while the second infiltration tripling in the Florida houses was attributed to system imbalances due to inadequate return-air pathways.

The importance of air-distribution system problems was further highlighted by a June 1989 ASHRAE symposium devoted entirely to the measured and predicted performance of residential air-distribution systems (Cummings and Tooley 1989; Lambert and Robison 1989; Modera 1989; Parker 1989; Robison and Lambert 1989).

Residential air-distribution system performance, especially duct-leakage problems, is particularly important in California. Slightly more than half of California's residences contain approximately 100,000 miles of ductwork, and virtually all new construction employs air-distribution systems. The particular importance of duct leakage in California stems primarily from the scarcity of basement construction in the state; ductwork is almost invariably contained in unconditioned attics and crawl spaces. Based on measured leakage data from 200 houses (80 in California) and measurements of actual driving pressures, the energy required to cool the air that leaks into and out of a typical duct system in a Sacramento house is between 1 and 2 kW (depending on the location of the ducts) of the peak-hour demand and 20% to 40% of the peak-cooling-day consumption (Modera 1989). Calculations show that the same leakage creates approximately 1 kW of peak heating demand and 2,000 to 3,500 kWh of annual electricity consumption for a heat-pump–heated house in Sacramento (Modera 1989).

In addition to the energy and peak-demand implications, leaky duct systems have been demonstrated to double air-infiltration rates when the distribution system is turned on, accounting for 20% to 40% of the average annual ventilation of residences (Gammage et al. 1986; Modera 1989).

These results made a strong case for careful examination of residential air-distribution systems' impacts on:

- The energy consumption and peak demands in California.

- The effectiveness of California's Title 24 energy code.
- The accuracy of state energy and demand forecasts.
- The ventilation rates providing indoor air quality in California residences.

PROJECT GOALS AND OBJECTIVES

The objectives of the planned three-year research effort on residential air distribution are to:

- Obtain representative data on the implications of air-distribution systems for residential energy consumption, ventilation, and peak power demand in California.
- Develop, test, and evaluate the cost-effectiveness of alternate approaches to problems with residential air-distribution systems for both new and existing buildings (including duct installation standards, sealing technologies, and non-air-distribution systems).
- Deliver a field-tested retrofit package for residential air-distribution systems to California utilities and other residential audit and retrofit groups.
- Provide a technically and economically defensible analysis of residential distribution system options for new buildings and a set of recommendations for California's Title 24 residential energy code.

APPROACH

Three potential inadequacies are usually identified in residential air-distribution systems:

1. Leakage between the ducts and their surroundings (particularly ducts in unconditioned spaces).
2. Excess infiltration and temperature imbalances due to improper balancing of supply and return flows.
3. Heat conduction through the duct surfaces (particularly through ducts in unconditioned spaces), including transient effects.

The focus of the first phase of this project—quantifying the impacts of residential air-distribution systems in California—involved separating these inadequacies. Three tasks were required to do that:

1. A telephone survey of HVAC contractors.
2. A field study to characterize California air-distribution system performance and retrofit potential.
3. Simulation-based analysis of peak-load mitigation and energy conservation potential.

HVAC CONTRACTOR SURVEY

The HVAC contractor survey was used to determine the relative frequency of use of air-distribution system options (sheet-metal ducts, flexible ducts, fiberglass ducts) in both new and existing houses in California. The purpose of this effort was to ensure that the buildings examined in the field study represented an appropriate mix of the California stock. The survey effort was directed primarily toward Northern California because data from a recently completed survey of more than 60 builders in Southern California could be used (Modera 1990).

FIELD STUDY

Although preliminary studies have indicated large potential impacts of distribution systems, a more directed field study to characterize air distribution in California residences was needed before embarking on larger-scale air-distribution retrofit efforts or implementing new distribution-system protocols in Title 24. This effort consisted of comprehensive measurement and analysis of distribution-system performance in 31 houses chosen to be representative of the stock identified in the builder and HVAC contractor surveys. The study's objectives were to characterize the physical and operating conditions of typical air-distribution systems in California houses and to provide the data needed to develop an appropriate retrofit protocol and recommendations for new construction. The study measured:

- Distribution-fan flow.
- Leakage, including that from envelopes, supply ducts, and return ducts. The relative importance of leakage at the furnace cabinet and at register penetrations was also qualitatively determined.

  Duct leakage was measured using two techniques, both of which were incorporated into a proposed American Society for Testing and Materials (ASTM) standard on field measurement of duct leakage. A third, greatly simplified technique for quantifying duct leakage was also used in each house; however, its performance was not analyzed for this report.
- Duct pressure during normal fan operation. This included pressure-differential measurements across the supply plenum, across the return plenum, just inside the supply registers nearest and furthest from the plenum, and just inside the return plenum.

- Pressure imbalance. This included pressure-differential measurements across the envelope and between zones, with the distribution fan on and off, and with interior doors open and closed.

- Ventilation rates with the distribution fan on and off. Rates were measured with a single tracer gas in all houses.

- Temperatures (indoor, outdoor, attic, and crawl space) with the distribution fan on and off. The attic and crawl-space measurements helped verify the assumptions used to analyze duct-leakage and duct-conduction energy implications.

- Duct temperatures during normal equipment cycling, including those in the supply plenum, in the return plenum, and just inside the supply registers nearest to and furthest from the plenum. These temperatures were used to estimate conductive losses from the ducts.

The field measurements were used to test the appropriateness of the assumptions made in earlier analytical efforts; quantify the relative importance of duct leakage, pressure imbalances, and conduction losses in typical California houses; and provide the input data needed for future simulations. They will also be used to identify the most appropriate elements for retrofit protocols.

The diagnostic measurement protocol developed for the field measurements consisted of a two-day, two-person procedure based on computer-controlled experiment prompting and data acquisition. Assuring high-quality data while minimizing the measurement cost per house meant developing an automated-instrumentation, data-acquisition, experimental-control system specifically for this field study. The system developed was based on a single instrumentation rack filled with:

- Tracer-gas injection and sampling equipment.

- Multiplexed and fixed-purpose pressure measurement equipment.

- A data-acquisition/control system (shown in Figure 1).

The system interface is a personal computer programmed to step the operator through the full series of diagnostic measurements. The system is programmed to take simultaneous time-averaged temperature, pressure, flow, and concentration measurements and record those measurements directly on the computer's hard disk. This operation reduces both instrumentation- and operator-induced uncertainties. To further minimize field-technician errors, the protocol includes step-by-step instructions for installing and measuring sensors. Also included are illustrations of sensor installations and building configurations (see Figure 2), photographic documentation lists, and building documentation instructions.

SIMULATION MODEL

The major objective of the simulation-based analysis was to evaluate peak-load mitigation and overall energy-conservation potential for improved distribution systems. This required simulation of the building envelope with a thermal model and accurate modeling of leakage-induced air flows, air flows created by system imbalances, and conduction heat losses from the ducts. This modeling was accomplished by interfacing DOE-2 (Birdsall et al. 1990), an hour-by-hour thermal simulation model, with MOVECOMP (Herrlin 1990), a multizone air-flow network model. Development and application of the simulation tool are described in detail in Unander (1991), the salient points of which are summarized in the following paragraphs.

The simulation tool being used for the air-flow modeling is the MOVECOMP multizone air-flow network model. To use this model for our purposes, we needed to specify all the air-leakage characteristics of the distribution system, the building envelope, the attic, the crawl space, and the garage, as well as the internal air-flow characteristics of the distribution system. The house with the chosen characteristics was implemented in the model by defining a set of uniform-pressure zones (pressure nodes) connected by specified air-flow resistances. To describe the pressure field in the duct system adequately, we settled on one node for every 3 m (10 ft) of duct, which corresponds to approximately 30 pressure nodes for the duct sys-

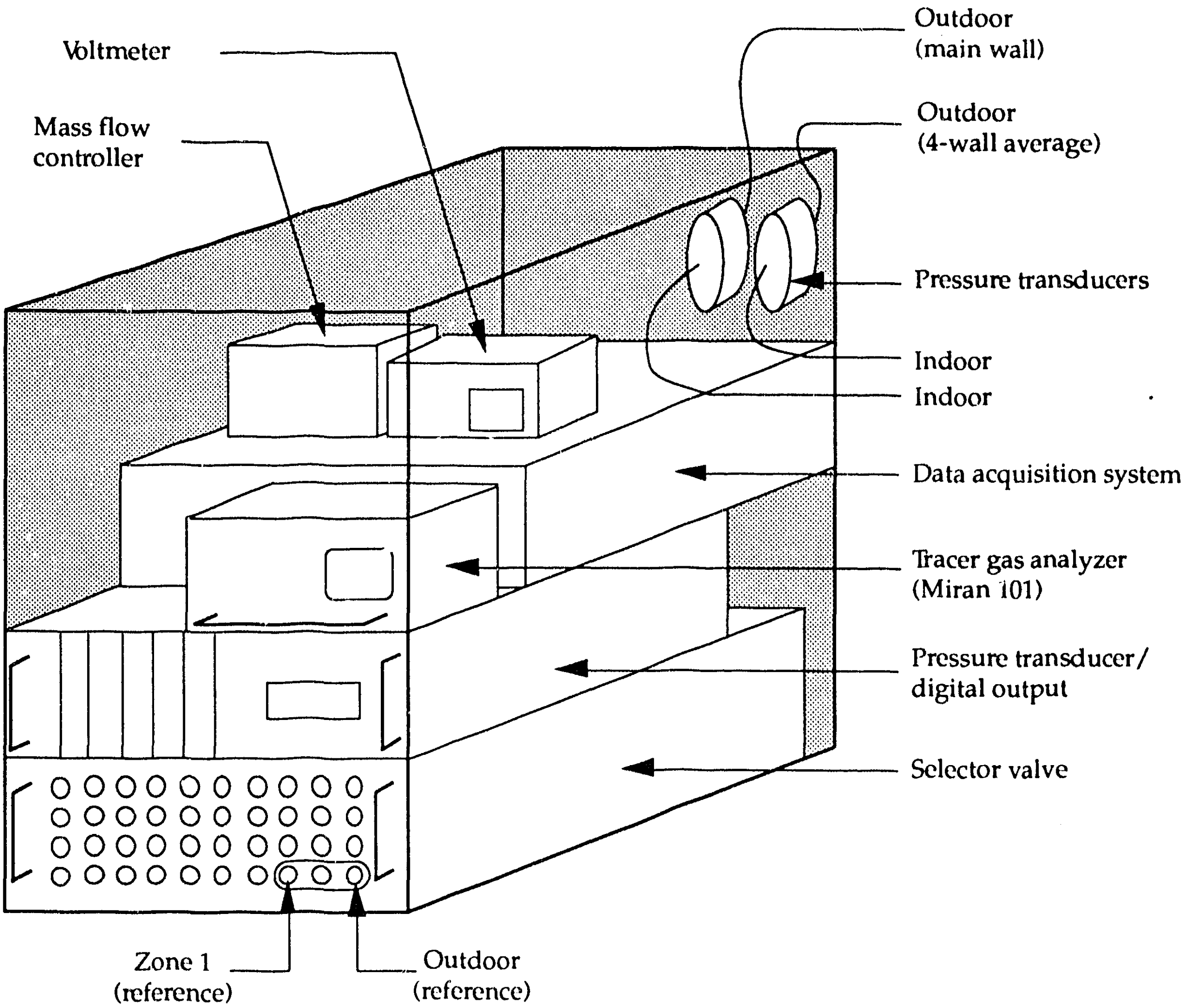


Figure 1. Schematic representation of the instrumentation rack used for the field study of residential air-distribution systems.

tem. In addition, six nodes were required to describe the interior zones of the house; one node was used for the attic, one for the crawl space, and one for the garage.

The leakage data required to describe the interconnections among the pressure nodes was obtained from the Lawrence Berkeley Laboratory (LBL) air-leakage database (Modera 1986) as well as from more recent measurements made by LBL, the Florida Solar Energy Center, and Lambert Engineering, Oregon (Cummings and Tooley 1989; Modera 1989; Robison and Lambert 1989). The input data was constructed in a modular manner to allow for easy modification based on the results of the field study. Based on this input data, two prototype simulations have been constructed and run: one modeling air flows while the distribution fan is operating, the other modeling air flows with the fan off.

To simulate the operation of the duct system and its interaction with the house, we modeled energy transfer between the ducts and their surrounding zone (attic or crawl space) using a combined heat- and mass-transfer simulation program (THERM-

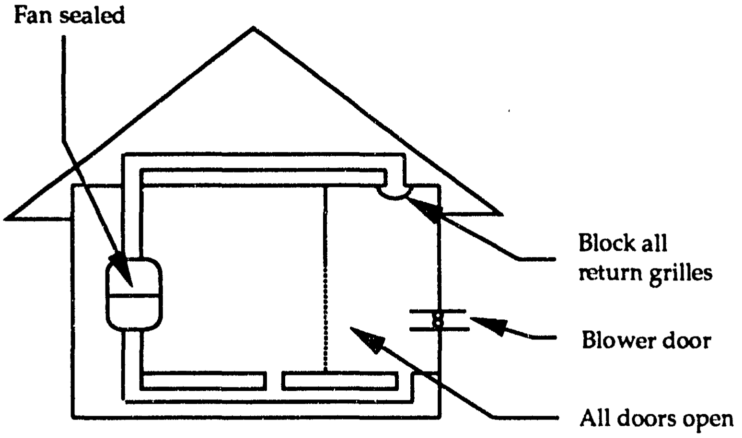


Figure 2. A sample leakage-test configuration used in the field study. This configuration is used to measure supply-duct and building-envelope leakage. Supply-duct leakage is measured by subtracting the results of an envelope-only configuration (all supply and return grilles blocked) from the results of this configuration.

PROG) specifically developed for the ducts. The attic and crawl-space temperatures are obtained from DOE-2 interactively, based on applying the energy transfer between the duct and the zone in which it is located. This process takes into account the partial recovery of duct heat and mass transfer; however, the simulation does not take into account the effects of the thermal mass of the duct system, the impacts of the duct system on air-conditioner or furnace efficiency, or the energy implications of the distribution-system fan.

THERMPROG also calculates the overall duct-system efficiency, including leakage and conduction, for each hour of the year, where duct-system efficiency is defined as the energy delivered to the house divided by the energy delivered by the furnace or air conditioner. A schematic flowchart of the complete simulation tool is depicted in Figure 3.

The building chosen for the simulations was a slightly enlarged version of the single-story California ranch house traditionally used for Title 24 energy calculations. This prototype house uses the same floor plan, has 1,540 ft^2 rather than the traditional 1,384 ft^2, and includes an attached garage. Increasing the floor area is consistent with the trend in California construction, and adding the garage stems from the results of the HVAC contractor survey (described in the next section). The duct system was assumed to have R-4 insulation and to have the supply ducts located in the attic; both assumptions are consistent with the contractor survey and field-study results. The return duct was conservatively assumed to be located in the crawl space, which is the most efficient location for cooling-season operation and an average location for the heating season. An exterior elevation and plan for the prototype house are depicted in Figure 4, and the duct layout is shown in Figure 5.

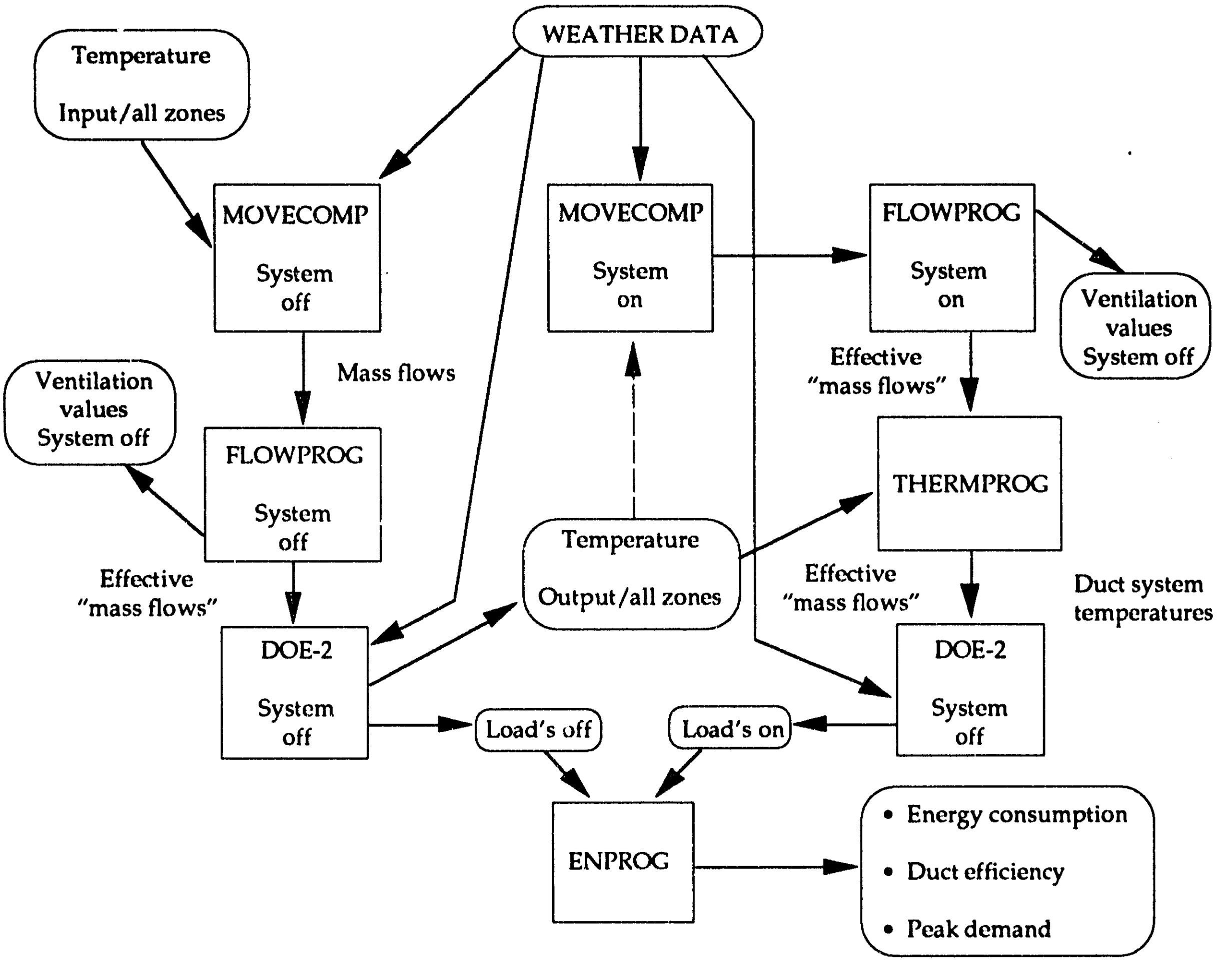
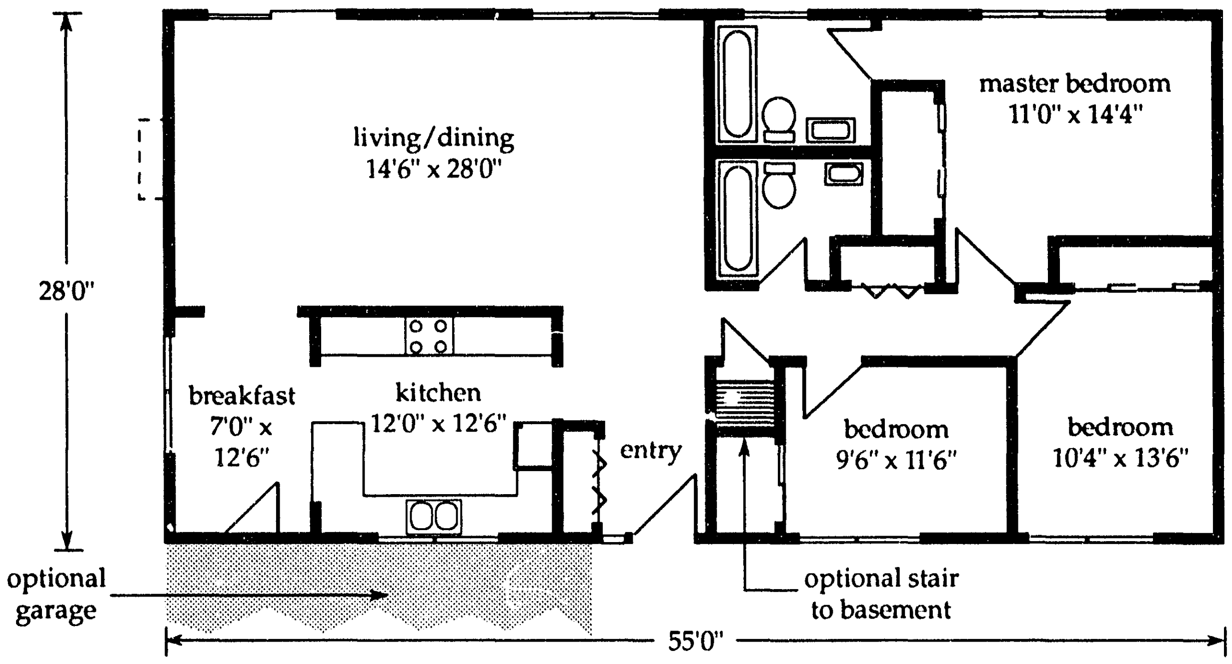
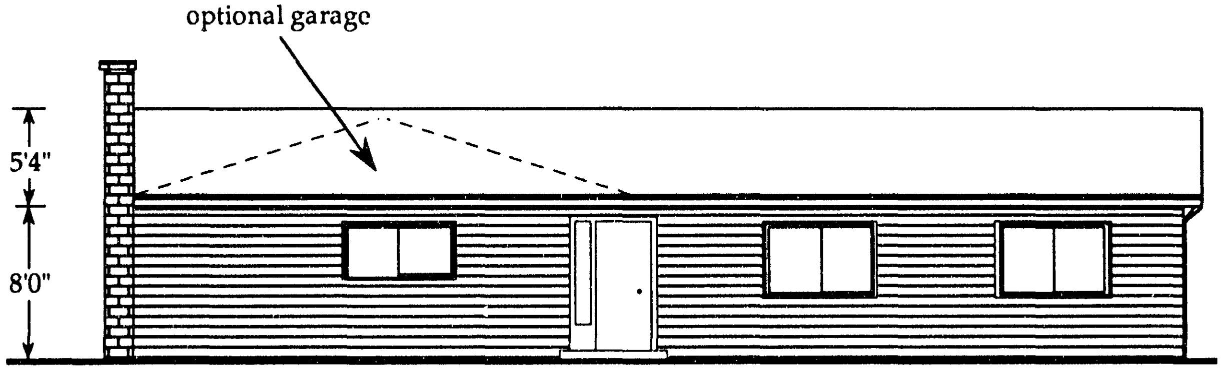


Figure 3. Schematic flowchart of programs used for simulating the performance of residential air-distribution systems.

Floor Plan



Front Elevation



Scale 1/10" =1'0"

Total floor area 1,540 ft²

Figure 4. Floor plan of the prototype building used for simulating the performance of residential air-distribution systems.

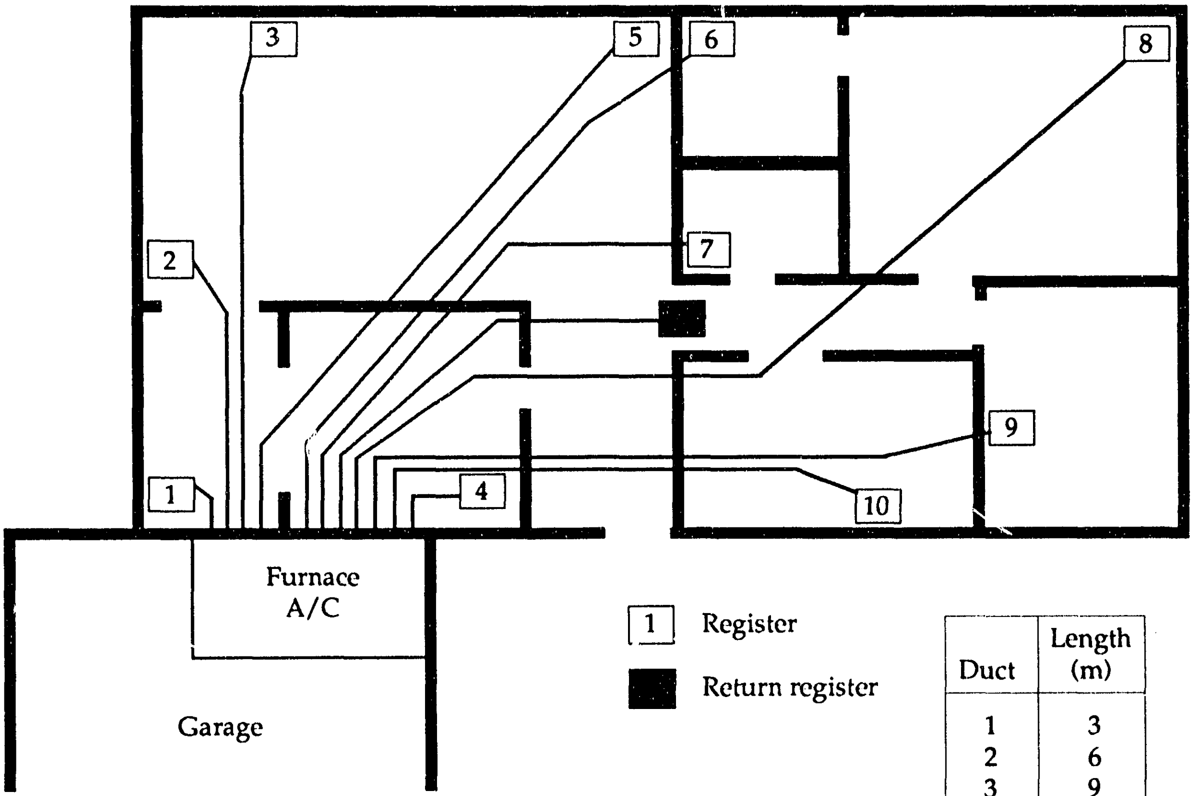


Figure 5. Layout of the duct system in the prototype building used for simulating the performance of residential air-distribution systems.

Duct	Length (m)
1	3
2	6
3	9
4	3
5	9
6	12
7	9
8	15
9	12
10	9
R	9

]

HVAC CONTRACTOR SURVEY

An HVAC contractor survey involving a 44-question telephone interview was completed before the field study began. Contractors from both Northern and Southern California were recruited from the business-to-business Yellow Pages and from a list of contractors identified by the University of California at Los Angeles as part of an earlier project examining zone conditioning in California. Ten residential HVAC contractors, who install a total of approximately 18,000 systems per year in California, were surveyed. The following are some of the more significant results extracted from the responses:

- More than 80% of the duct systems are installed in attics.
- Approximately 60% of the heating/cooling units are installed in garages; the remainder are installed in attics.
- The vast majority (85%) of the installed ducts are flexible dual plastic cylinders that use a metal spiral for support and are separated by approximately one inch of fiberglass insulation. The remaining duct systems are either aluminum or sheet metal, usually with one inch of fiberglass insulation.
- Almost 90% of the installed ducts have nominal insulation values of R-4 or higher.
- Approximately three-quarters of the installed ducts are sealed with cloth duct tape only.
- The HVAC contractor typically determines the materials and layout for the duct system, whereas the general contractor typically determines the undercut (air-flow resistance) of internal doorways.
- Approximately 75% of the contractors said they would be interested in being paid to make post-installation performance checks.
- Approximately 60% of the contractors said they have the capability to install ducts within the conditioned space or to install hydronic or refrigerant distribution systems.

A number of these results, such as the locations of the ducts and heating/cooling equipment as well as the insulation level of the ducts, were used to define the prototype house to be used in the performance-simulation effort. Perhaps the most interesting result, however, is the apparent interest of the contractors in making post-installation performance checks. If this is in fact the case, the technology-transfer portions of this project could prove quite fruitful.

FIELD STUDY

The field-diagnostic measurement procedure was run in 31 houses: nine in San Diego, four in Sacramento, and 18 in the San Francisco Bay Area. Of these houses, 19 were built prior to 1980. This report presents the reduced data in summary form for most of the key system parameters examined (the house characterization data will be analyzed further when the retrofit protocols are developed). The following sections summarize the data for the significant parameters associated with each of the distribution-system loss mechanisms:

- Duct leakage
- Duct conduction
- Supply/return-flow imbalances.

Duct Leakage

Duct leakage was measured in each house using three techniques, two of which are currently incorporated in a proposed ASTM standard measurement protocol. The first of these techniques (Method A) uses subtraction of leakage values calculated from blower-door measurements with and without the duct system sealed to obtain the duct leakage. The second technique (Method B) uses a direct measurement of the flow through the duct leaks together with auxiliary duct-pressure measurements to obtain the duct leakage. Method A suffers from elevated uncertainties in determining the flow, whereas Method B suffers from elevated uncertainties in determining the appropriate duct pressure.

The third technique is a rather simplified procedure that uses changes in blower-door flows associated with turning on the fan, together with duct pressure measurements, to estimate supply- and return-duct leakage. An analysis of this technique, along with comparisons of the three techniques with tracer-gas results (see below) and more detailed examinations of each of the measurement protocols, is underway.

Some of the envelope- and duct-leakage measurements obtained by Method B are summarized in Table 1 for both pre-1980 and post-1979 construction. A number of conclusions can be drawn from these results. First, it seems that the specific leakage area of the building envelope dropped by approximately 35% in the post-1979 construction, a result that, while not conclusive, suggests that California houses are getting tighter. Although the sample size is small, the standard deviation of the post-1979 data is also small; in addition, the mean of the pre-1980 data (which has a large standard deviation) is lower than an earlier estimate of pre-1980 California construction (120 houses), suggesting that the apparent increase in envelope tightness may be real. On the other hand, it does not seem that duct tightness has improved with time; the data suggests that, if anything, both supply- and return-duct leakage have increased. Moreover, the average total duct leakage is 145 cm^2 for pre-1980 construction and 176 cm^2 for post-1979 construction; both numbers are higher than the 140 cm^2 used in the simulations.

Finally, as observed in earlier studies, the standard deviation of the measured leakage is high (50 to 100%), suggesting that retrofit programs would benefit from pre-retrofit measurements of duct leakage. The supply/return leakage fractions in Table 1 are also consistent with earlier field results (Modera 1989) in that, despite their significantly smaller surface area, return ducts typically have more leakage than supply ducts. This result takes on even more significance when you consider that return-duct pressure differentials average twice those of the supply side during system operation (see Table 2) and that the energy implications of return leaks in attics are even greater than those of supply leaks.

A more in-depth analysis of the duct-leakage measurements is being performed for several reasons, including:

1. The simulation work suggests that duct leakage is the largest source of duct-system inefficiency.

2. The data set gathered in this project will significantly affect an ASTM standard for measuring duct leakage by Method A and Method B.

3. The development and standardization of a field technique for measuring duct leakage could have relatively short-term implications for California Title 24 energy budget compliance and home energy rating systems.

The in-depth analysis of the duct-leakage data includes cross-comparisons of the two measurement techniques and examines the factors affecting each technique's precision and accuracy.

Concerning the issue of measurement accuracy and precision, the choice of parameters by which to characterize duct leakage plays an important role. In general, the flow through duct leaks is modeled with a power-law relationship between pressure differential and flow. This representation involves two parameters, the flow coefficient and flow exponent, which together can be expected to characterize the flow over a fairly wide range of pressure conditions. However, to create a practical yardstick of performance, we need to characterize duct leakage with a single parameter. For building envelopes, the chosen parameter is typically the effective leakage area at 4 pascals (Pa). That particular reference pressure was chosen because it is representative of the naturally occurring pressures across leaks in the building shell. Leakage measurements are performed at pressure differentials between 10 and 50 Pa to avoid interference by the same naturally occurring pressures. Determining the effective leakage area at 4 Pa requires an extrapolation of the pressure/flow relationship outside the higher pressure range (10 to 50 Pa) in which that relationship was determined.

Duct-system driving pressures are similar to those for the building envelope when the system is not operating; however, when the distribution fan is running, the driving pressures are significantly higher and duct leakage causes most of the impact. As shown in Table 2, the driving pressures for duct leakage during system operation average 29 Pa for the supply side and 57 Pa for the return side. Thus, as the uncertainty in the measured pressure-flow relationship for ducts is lowest near the middle of the measurement range (Persily 1983; Persily and Grot 1985) and the most important driving pressures for duct leakage are nearer to that portion of the measurement range than to 4 Pa, a reference pressure of 25 Pa was chosen for the ASTM standard (computation of the 4-Pa leakage area is also suggested to allow direct comparisons with envelope leakage).

Table 1. Envelope- and duct-leakage data by year of construction.

	Pre-1980		Post-1979	
Characteristic	Mean	Std. Dev.	Mean	Std. Dev.
Number of houses	19		12	
Floor area (ft^2)	1740	530	1990	390
Specific envelope leakage area[1] (cm^2/m^2)	6.6	2.5	4.5	0.6
Supply-duct leakage area (cm^2 at 4 Pa) (Pressurization) Method B	68	28	78	50
Supply-duct leakage area (cm^2 at 4 Pa) (Depressurization) Method B	68	38	85	56
Return-duct leakage area (cm^2 at 4 Pa) (Pressurization) Method B	77	52	94	72
Return-duct leakage area (cm^2 at 4 Pa) (Depressurization) Method B	77	74	94	70

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[1] Normalized by floor area

Table 2. Pressure differences between ducts and their surroundings during normal system operation.

Location	Mean Value (Pa)	Standard Deviation (Pa)	Minimum (Pa)	Maximum (Pa)
Supply plenum	46	28	9	138
Supply duct average	29	17	7	83
Return plenum	–88	43	–14	–181
Return duct average	–57	31	-5	–126

Comparing pressurization and depressurization data for Methods A and B for both return and supply leakage measurements demonstrates the improvement in precision associated with increasing the reference from 4 to 25 Pa. As evidenced by the data in Table 1, no significant bias is apparent between pressurization and depressurization results at 4 Pa. This was also found to hold at 25 Pa. On the other hand, graphical comparisons of pressurization and depressurization results at 4 and 24 Pa (Figures 6 through 9) show a significant decrease in scatter for the 25-Pa results, which is indicative of the increased precision at the higher reference pressure.

A cross-comparison of duct-leakage areas determined by Method A (blower-door subtraction) and Method B (direct duct-flow measurement) is plotted in Figures 10 and 11. These figures show the expected correlation between the two independent leakage estimates; however, there seems to be some positive bias of the Method B results relative to the Method A results, particularly for the return-duct leakage. Potential reasons being investigated include:

- Different impacts of leaks between the ducts and the house on the two techniques.
- Reduced pressure differentials across the ducts relative to indoor-outdoor pressures during Method A tests.
- Potential biases in pressure differentials used for Method B tests.

To estimate the impacts of duct leakage on distribution-system performance, we need both the leakage characteristics of the ducts and the pressures driving the flow through those leaks. These driving pressures were measured at five locations in every duct system during normal fan operation (supply plenum, nearest supply register, furthest supply register, return plenum, and return register) and are summarized in Table 2.

The results in Table 2 agree with earlier estimates of duct-leakage pressure differentials (Modera 1989), confirming that the infiltration, ventilation, and energy impacts of duct leaks should be far more significant than those of building-envelope leaks. These results also suggest that characterizing duct leaks at a reference pressure of 25 Pa is actually more appropriate than at the more uncertain 4 Pa.

Another way to quantify the impact of duct leakage in residences is to measure the whole-house air exchange rate directly, with the system fan on and off. This was done in each of the 31 houses by analyzing tracer-gas concentration decays with the distribution-system fan on and off. The results of these measurements, summarized in Table 3, confirm and even exceed earlier estimates of the importance of duct leakage in residential house infiltration and ventilation. They also suggest that natural infiltration rates during shoulder periods are often lower than most standards would allow. Efforts to compare measured magnitudes of duct leakage and driving pressures with measured duct-induced infiltration rates are under way.

Figure 6. Supply-duct leakage area measured by Method A during depressurization versus pressurization at a reference pressure of 4 Pa.

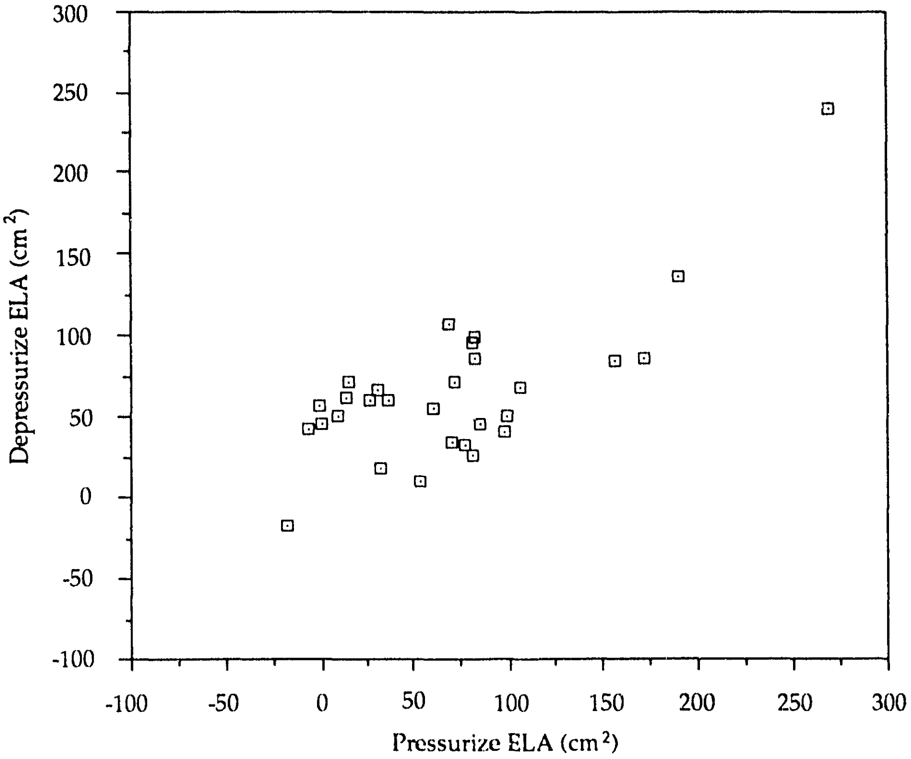
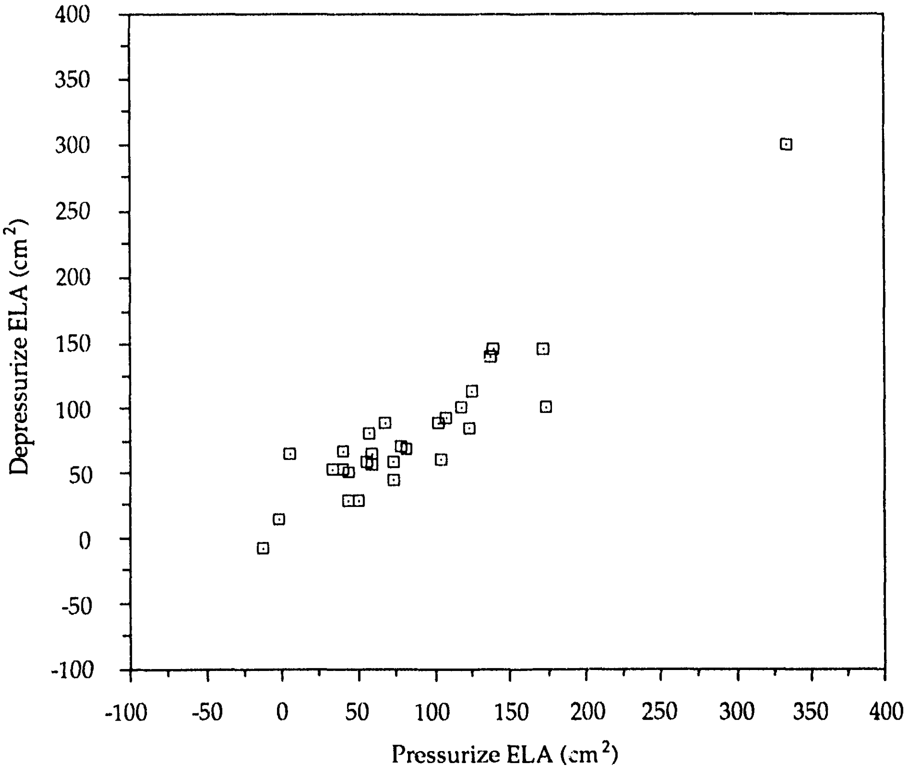


Figure 7. Supply-duct leakage area measured by Method A during depressurization versus pressurization at a reference pressure of 25 Pa.



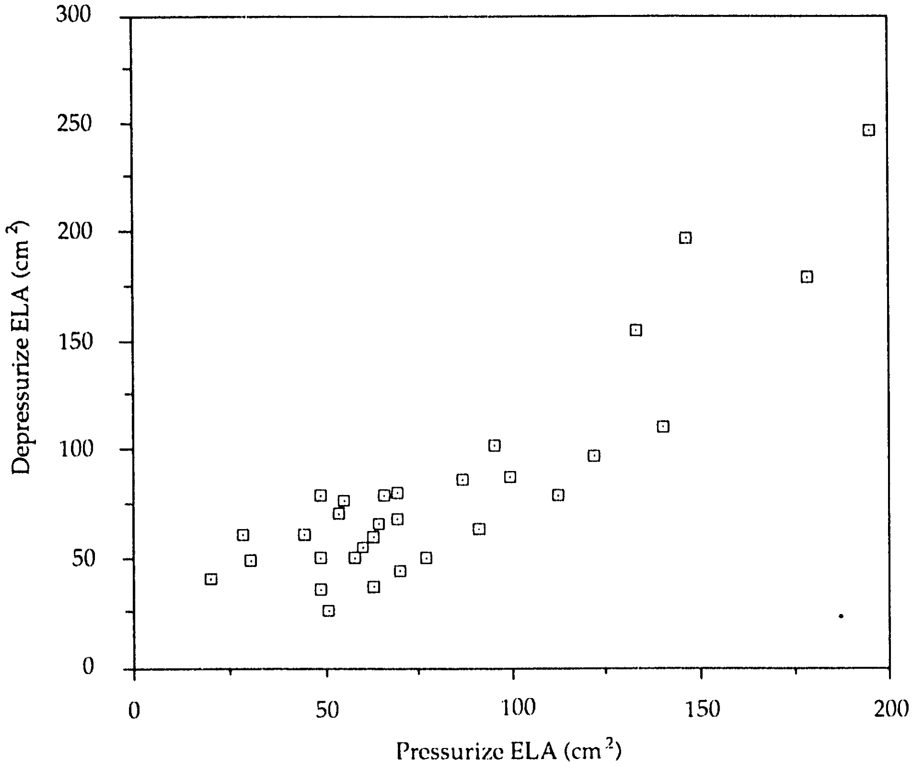


Figure 8. Supply-duct leakage area measured by Method B during depressurization versus pressurization at a reference pressure of 4 Pa.

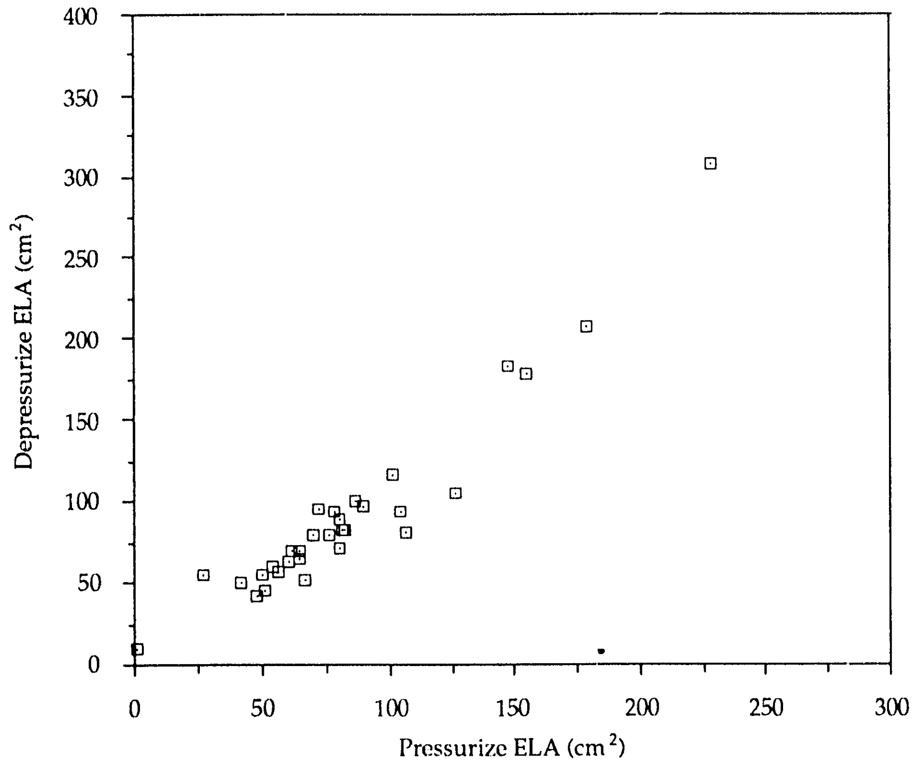


Figure 9. Supply-duct leakage area measured by Method B during depressurization versus pressurization at a reference pressure of 25 Pa.

Figure 10. Supply-duct leakage area measured by Method B versus Method A at a reference pressure of 25 Pa.

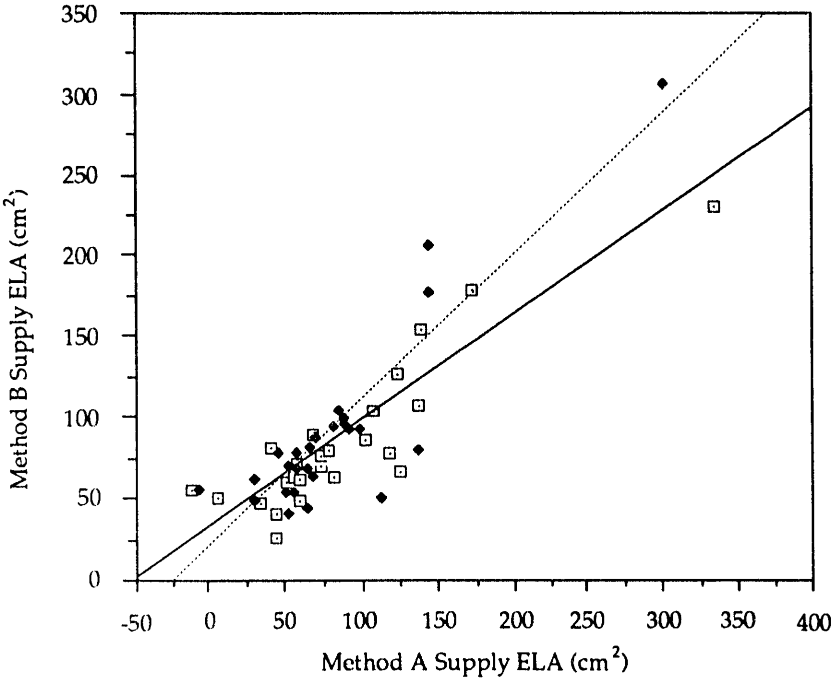


Figure 11. Return-duct leakage area measured by Method B versus Method A at a reference pressure of 25 Pa.

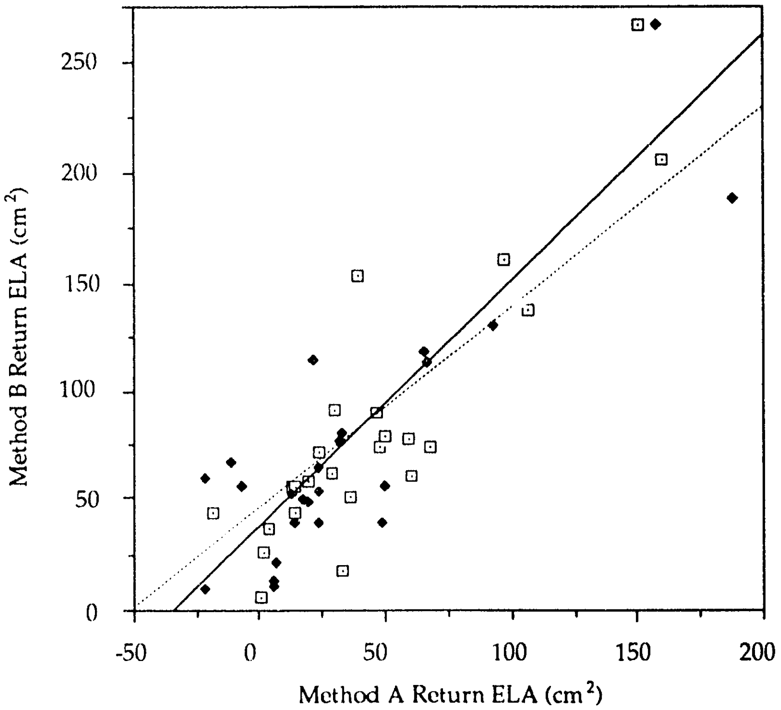


Table 3. Whole-house air exchange rates with distribution fan on and off.

Parameter	Mean Value (ACH)	Standard Deviation (ACH)	Minimum (ACH)	Maximum (ACH)
Whole-house air exchange (system off)	0.24	0.15	0.01	0.57
Whole-house air exchange (system on)	0.69	0.29	0.18	1.69
Whole-house air exchange (on - off)	0.45	0.31	0.02	1.50

Duct Conduction

The impacts of supply-duct conduction losses were estimated for each house based on measured air temperatures at the supply plenum, nearest supply duct, and furthest supply duct. The results of these analyses are summarized in Table 4. The fractional energy loss by conduction in Table 4 is computed by dividing the average temperature drop through the longest and shortest ducts by the temperature rise across the furnace. Because the temperature at the end of a supply duct is not significantly affected by leakage from that duct (except in the impact of reduced flow rates on residence time and on convective heat-transfer coefficients), this technique isolates the conduction losses of the supply ducts (the combined heat and mass-transfer problem was solved for the simulation code).

The results in Table 4 suggest that conductive heat losses from existing ducts are significant. The table also suggests that conduction losses are higher than those obtained in some preliminary simulation analyses, averaging 23% rather than the 13% obtained in the simulations. The principal reason for this discrepancy is probably the fact that the ducts in the field were not insulated to R-4, as was assumed in the simulations. The average duct insulation thickness observed in the field was 2.1 cm (0.84 in.); the uniform mechanical code suggests that one inch of external insulation has an R-value of 2.1 and one inch of fiberglass insulation has an R-value of 3.1, based on standard wall insulation numbers. The simulation numbers may not agree with the field results for a number of other reasons:

- The ducts in the field might be significantly longer than those assumed in the simulations.
- The simulation results are based on comparison of the overall duct efficiencies with R-4 and R-40 insulation, a process that takes into account the interaction between duct leakage and conduction.
- The temperature differentials driving conduction might be significantly higher in the field.
- The residence time of the air in the ducts might be longer in the field.

The average length of the longest supply duct in the field was 10.8 m, while the longest supply duct in the simulations was 12 m. The other potential contributing factors are under investigation; they include normalization of the data based on the measured temperature differentials between the ducts and their surroundings and on simulations of the measurements made in the field. The temperature differential normalization is expected to reduce the rather large scatter in the fractional conduction losses. The explanation for field/simulation discrepancies notwithstanding, these field results suggest the potential for considerable energy savings if the insulation value of residential ducts is increased.

Table 4. Measured conduction losses in supply ducts (26 houses).

Parameter	Mean Value	Standard Deviation	Minimum	Maximum
Temperature rise across furnace (°C)	37	9	26	62
Temperature drop through ducts (°C)	9	8	1	34
Fractional energy loss by conduction (%)	23	14	4	55

Supply/Return-Flow Imbalances

The field study collected data on the following parameters, which can be used to characterize the impact of closed internal doors on duct-system performance:

1. The indoor-outdoor pressure differentials in each zone that are created by the operation of the distribution-system fan.

2. The changes in supply- and return-duct pressures caused by closing the internal doors.

3. The heights of all undercuts of internal doorways.

The indoor-outdoor pressure differences created by closing the doors during distribution-fan operation were measured for each of the 144 zones encountered in the field study. The results, summarized in Table 5, indicate that closing ininternal doors should have a significant impact on the infiltration rate of a house because typical driving pressures for natural infiltration are 1 to 4 Pa. The large scatter in these results is not surprising considering the large observed variability in door undercuts, the additional variability introduced by the variations in supply flows to individual zones, and variations in envelope leakage. In one house, two similar-size zones with approximately equal supply-air flow rates and door undercuts were measured to have pressure differentials of 2.7 and 17.5 Pa. This large discrepancy stemmed from the fact that one zone had new, tight windows and the other had the original leaky windows, indicating that the pressure differential is only serving as a surrogate for the desired flow impacts.

Moreover, in four houses, zones that did not have return grilles were actually depressurized when the doors were closed. Although this result seems counterintuitive, it is real. The house with the largest depressurization of supply-only zones had a unique internal configuration in which the return was in a hallway that was separated from all the supply registers when the doors were closed. This created an extreme depressurization of the return zone (–17 Pa) and subsequent depressurization of the supply zones that had the best connections to the return zone (in other words, large door undercuts). The other depressurized supply-only zones were found in houses with large supply-duct leaks relative to return-duct leaks. In such cases, the entire house tends to be depressurized when the fan turns on, even if the internal doors are open.

A comparison of supply- and return-duct pressures with the internal doorways closed and open indicated that the pressure differentials across the ducts typically increased when the internal doors were closed. The average pressure differential across supply leaks increased by approximately 10%, whereas the average pressure differential across the return increased by approximately 6%. These results, combined with our knowledge of the flow exponent of duct-leakage sites, suggest that closing the internal doors will increase the leakage flows through ducts by approximately 4% to 7%.

The heights of door undercuts for the 144 doors measured in the field study were found to vary

Table 5. Indoor-outdoor pressure differences for various zones resulting from closing all interior doors.

Location	Mean Value (Pa)	Minimum (Pa)	Maximum (Pa)
Supply-only zones	6.0	-5.3	23.7
Return-only zones	-2.7	17.4	0.2

between 0 and 1.4 in. (35 mm), with a mean value of 0.52 in. (13 mm) and a standard deviation of 0.30 in. (7.6 mm). These values suggest that the assumption of 0.4 in. (10 mm) for the simulations was not unreasonable.

SIMULATION MODEL

The multizone air-flow and thermal-simulation tool developed for a residential air-distribution system was applied principally to the newly constructed California ranch house described earlier; however, the effects of several potential key issues were also examined, including the effects of changing from a well-insulated envelope to a poorly insulated envelope and from a crawl-space return duct to an attic return duct. Similarly, the analyses to date have focused primarily on the combined effects of duct leakage and duct conduction, although some preliminary simulation-based examinations to isolate duct leakage from conduction and to estimate the impact of closing internal doors were performed (see the earlier discussions of field measurement of interzone pressure differentials due to door closures).

In summary, the UA-value of the envelope was not found to have a large impact on the percentage of energy use associated with duct inefficiencies, while the choice of slab-on-grade versus crawl-space construction (or, more specifically, the use of attic rather than crawl-space returns) was found to have a large impact on cooling-energy use and peak demand. The results of the simulations performed for the crawl-space-return/attic-supply configuration in new and existing houses are summarized in Tables 6 and 7, respectively. The results in Table 6 suggest that the energy implications of a residential air-distribution system are significant. Approximately one-third of the heating bill in a Sacramento ranch house appears to result from inefficiencies in the air-distribution system, while between 23% and 40% of the electricity consumption for cooling is due to distribution inefficiencies. Perhaps the most interesting result is the large cooling penalty associated with locating the return duct in the attic rather than in the crawl space. This examination of return-duct location indicated that for a poorly insulated house, cooling energy consumption increased by 28% when the return duct was located in the attic rather than in the crawl space. This type of installation occurs in most slab-on-grade houses, suggesting that cooling-energy and peak-demand impacts can be much greater for that type of construction. This will be an important result in the analysis of the effectiveness of potential retrofit protocols. On the other hand, the impact of return-duct location on heating is expected to be small because of the minor differences between attic and crawl-space temperatures in the winter.

The savings results in Table 7 are surprisingly similar to those in Table 6, suggesting that the UA-value of the building envelope does not have a large impact on the overall energy performance of the air-distribution system. These results suggest that it may be possible to characterize savings potential by a UA-independent efficiency, an idea that will be investigated in the work to follow.

The peak-load impacts of residential air-distribution systems were also examined based on the simulations; the results of this investigation are shown in Figure 12 for a well-insulated house on a peak Sacramento summer day. This figure indicates a peak electricity demand due solely to the leakage and conduction from the duct system of 0.8 kW; an additional 0.2 kW of demand would occur at the peak if the internal doors were closed. The relatively small effect of closing the internal doors may result from the fact that this is a crawl-space house. The implication is that the energy load caused by excess infiltration from the attic is somewhat compensated for by the excess infiltration from the relatively cool crawl space. Because the annual energy implications of closing internal doors turned out to be on the order of 2%, those simulations are being scrutinized.

In addition to investigating the energy impacts of air-distribution systems, the simulations can also be used to analyze the ventilation impacts of air-distribution systems. The ventilation results for a well-insulated house are summarized in Table 8. These numbers are consistent with earlier estimates of the impacts of leaky ducts and are somewhat higher than the results of the field study. Specifically, the distribution fan was simulated to increase infiltration by approximately a factor of 3, consistent with the results in Table 3 and with those quoted in earlier studies. However, the simulated average increase in infiltration due to fan operation of 0.67 ACH is higher than the average infiltration-rate increase of 0.45 ACH measured in the field study. The sources of this difference are under investigation. Also, despite the relatively short system on-time, a house with a typical air-distribution system (with the doors open) is suggested to have 37% more infiltration than a house without an air-distribution system; the latter just meets the ASHRAE Standard 62 level of 0.35 ACH. This is worthy of additional investigation because the field study indicates that newer houses are approximately 30% tighter than the house used for the simulations.

Table 6. Annual space-conditioning energy use in a new (well-insulated) Sacramento ranch house.[2]

System	Cooling (kWh)[3]	Heating (Therms)[4]
No ducts	980	87
Typical ducts	1270	130
Potential savings	290 (23%)	43 (33%)
Potential savings (with attic ducts)	640 (40%)	

Table 7. Annual energy use in an existing (poorly insulated) Sacramento ranch house.[5]

System	Cooling (kWh)[6]	Heating (Therms)[7]
No ducts	1200	370
Typical ducts	1560	530
Potential savings	360 (23%)	160 (30%)

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[2] Assuming enthalpic venting, cooling in May through October, heating in November through March, R-19 walls, R-30 ceilings, R-19 floor, double-pane windows, crawl-space return duct, and attic supply ducts.

[3] Assuming a COP of 2.93 (i.e., SEER = 10).

[4] Assuming an AFUE of 85% for the furnace or wall heater.

[5] Assuming enthalpic venting, cooling in May through October, heating in November through March, R-0 walls, R-11 ceilings, R-0 floor, single-pane windows, crawl-space return duct, and attic supply ducts.

[6] Assuming a COP of 2.34 (i.e., SEER = 8).

[7] Assuming an AFUE of 75% for the furnace or wall heater.

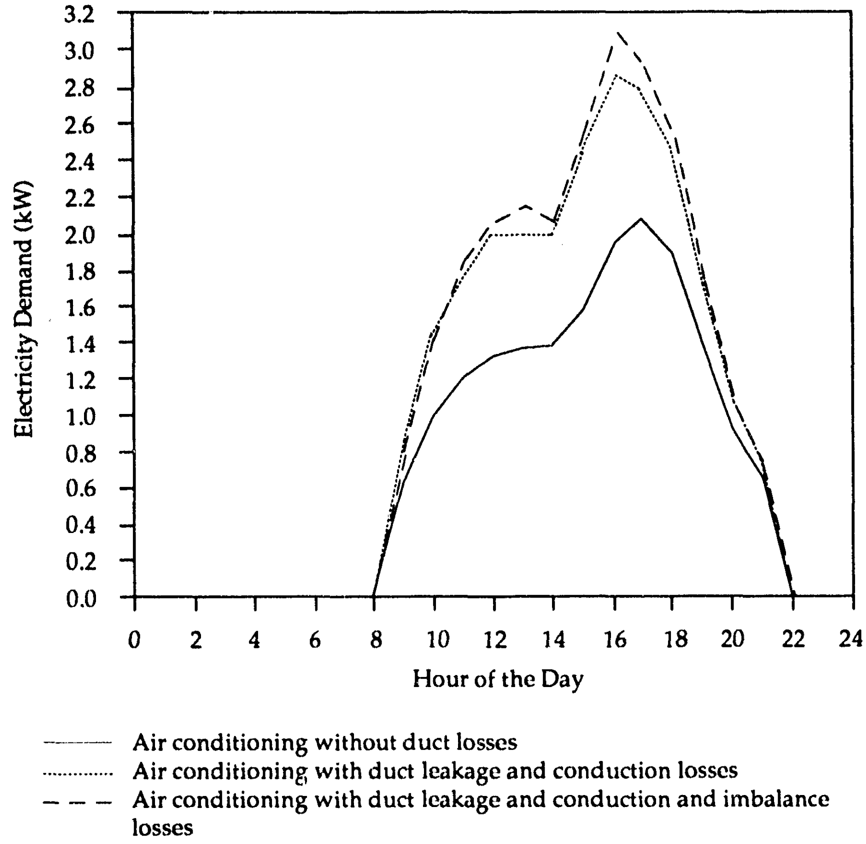

Figure 12. Simulated air-conditioner electricity demand for a peak cooling day in Sacramento. The three curves correspond to a house with room air conditioners with an EER of 10; a central air conditioner with an EER of 10 and typical attic ducts (R-4 and 140 cm^2); and a central air conditioner with an EER of 10, typical attic ducts (R-4 and 140 cm^2), and closed undercut (0.4 in.) internal doorways.

Table 8. Ventilation impacts of a typical duct system in a Sacramento ranch house.[8]

House Condition		Mean Air Change Rate (ACH)
Doors open	No ducts	0.35
	Distribution fan off	0.39
	Distribution fan on	1.06
	Typical year [9]	0.48
Doors closed	Distribution fan off	1.64
	Typical year [9]	0.51

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[8] Ignoring the effect of opening windows for thermal venting.

[9] The total time the system is on is 1,113 hours, corresponding to an annual average fractional on-time of 0.127, which was computed for doors open and assumed for doors closed.

CONCLUSIONS AND FUTURE DIRECTIONS

This report has described the results of the first phase of a multiyear research project to investigate ways to improve the efficiency of air-distribution systems in single-family detached residences in California. First-year efforts included:

- A survey of California HVAC contractors.
- A 31-house field study of distribution-system performance based on diagnostic measurements.
- Development of an integrated air-flow and thermal-simulation tool for investigating the performance of residential air-distribution systems.

Several conclusions can be drawn from the work presented. First, we can safely conclude that earlier examinations of air-distribution system performance did not exaggerate its importance. Both the field data and the simulation work indicate the significant impact of air-distribution systems on energy use and ventilation. We can also conclude that the Phase I efforts have significantly enhanced our understanding both of the distribution-system stock and of the tools available for analyzing its implications. More specifically, the age of the house, although it did seem to affect the air leakage of the envelope, showed no significant impact on the performance of the distribution system. Some tentative conclusions based on the simulation results were reached:

- The location of return ducts can have a dramatic impact on cooling-season energy performance, the duct efficiency being 17 percentage points lower for an attic return than for a crawl-space return.
- The UA-value of the building envelope does not seem to have a large impact on the overall efficiency of the air-distribution system.

Before general conclusions can be drawn, the field-study data must be used for more rigorous checks of the intermediate simulation results, and the simulations need to be repeated for a number of climate zones and system/house configurations. Also, energy-related aspects of air-distribution systems that have not yet been incorporated into the simulations will have to be included prior to final analyses of retrofit or new-construction policies. These include:

- The effect of the distribution system's thermal mass on its overall energy loss.
- The energy impacts of the distribution-system fan and its required on-time.
- The impacts of the air-distribution system on the efficiency of cooling equipment and, under some circumstances (such as when heat pumps are used), heating equipment.

Finally, the relative importance of the different loss mechanisms still needs to be sorted out—in particular, the interaction between conduction and leakage in the return and supply ducts.

In addition to continued simulation work, future efforts are expected to examine potential technologies and protocols for improving new and existing residential air-distribution systems as well as, in the longer term, alternatives to air distribution. The field characterization and simulation are also expected to be extended to multizone residential air-distribution systems.

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