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Authors

Dickerhoff, D J
Grimsrud, D T
Lipschutz, R D

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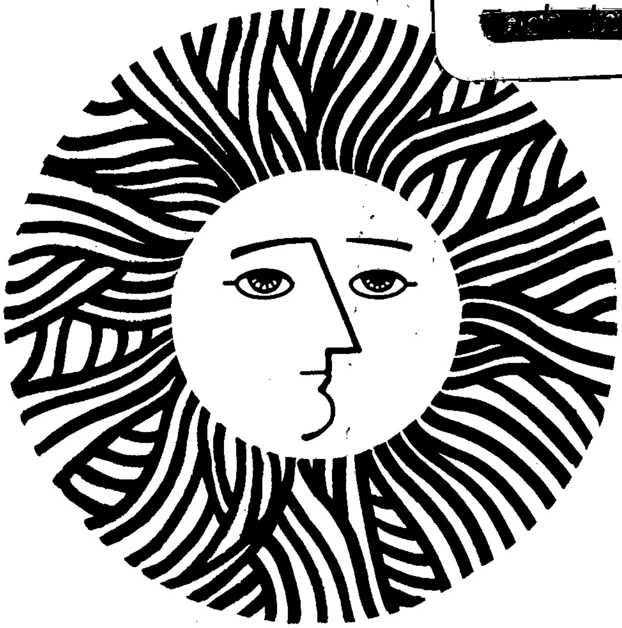

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ABSTRACT

The common approach to leakage area measurements in residential housing is through pressurization of an entire structure with a blower door. However, this technique does not provide quantitative measurements of the leakiness of individual building components. By pressurizing individual components, it is possible to determine the distribution of leakage within a structure. The studies described in this paper involved measurement of the leakage areas of fireplaces, bathroom and kitchen exhaust vents, electrical outlets and leakage in the ducts of forced air distribution systems. Component leakage measurements were made in a total of thirty-four houses in Atlanta, Georgia, Reno, Nevada and the San Francisco Bay area. Damperless fireplaces and ductwork were found to be the most significant sources of leakage in the western houses. In the Atlanta houses, where cooling loads dominate, the significant leakage area was in the ductwork of the distribution system for central air conditioning that passes through the unconditioned space in the attic and crawlspace.

Keywords: air infiltration, tracer gas, air leakage, pressurization, correlation, duct, blower, cooling, humidity

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INTRODUCTION

Air infiltration is a major source of energy loss in residential buildings during the heating and cooling seasons. Measurement of building leakage by fan pressurization allows a determination of the overall importance of infiltration in the building. By pressurizing individual building components, a quantitative evaluation of the relative leakiness of different parts of a building can be obtained. Knowing which building components are major leakage sites can be of great help in reducing energy loss by infiltration. To obtain this information, the Energy Performance of Buildings Group at Lawrence Berkeley Laboratory undertook a study of building components in order to find common leakage sites and to measure their effective leakage area. In previous studies [1-3] the leakage of doors and windows has been found to make up about 25% of the total leakage of the house. Consequently, the component leakage study focused on other leakage sites: fireplaces (with and without dampers and/or inserts with doors), bathroom and kitchen exhaust vents, electric outlets and heating and cooling ducts.

During 1980 and 1981, air leakage measurements were made on a total of thirty-four houses. Eight houses in Atlanta were measured as part of a project to assess the contribution of infiltration to summer cooling loads in the hot humid climate of the southeastern United States [4]. The only such measurements made in this region previously were designed to quantify the contribution of infiltration to winter heating loads [5]. Ten San Francisco Bay area houses were measured, three of them as part of a project to assess the effectiveness of polyurethane foam sealing of cracks in the building envelope during construction [6]. The remaining sixteen houses were measured specifically as part of the component leakage study in Reno, Nevada.

MEASUREMENT PROCEDURES

Component air leakages were measured using the blower-door fan pressurization technique [7]. This technique measures air leakage at imposed pressure differences, which are much greater than those associated with normal weather conditions. In order to measure the leakage of specific components, a duct containing an orifice plate (for measuring air flow) is attached to a smaller blower and sealed around specific leakage sites. The entire house is then pressurized with the blower door. The small blower is used to maintain the same differential pressure across the building envelope and the component, insuring that all air flow through the component is to the outside. This allows determination of the external leakage of the component. The leakage of the ducts, electric gaskets, and some of the fireplaces are found by measuring the whole house and then sealing the component and determining the reduction in the house effective leakage area. The measured leakage of these components have a larger uncertainity than those of the components which could be measured directly with the orifice plate system. Design ventilation openings that are not being measured are sealed, but all other penetrations, such as flue openings, are left unaltered.

The leakage of a structure or component can be characterized by a quantity called the "effective leakage area", and is defined by the equation below:

$$L = \frac{Q_4}{\sqrt{\frac{2}{\rho}\Delta P_4}} \qquad (1)$$

where:

L is the effective leakage area (m^2)
Q_4 is the air flow at 4 pascals pressure (m^3/s)
ρ is the density of air ($2.5\ kg/m^3$) and
ΔP_4 is 4 pascals pressure across the leakage site.

The air flow at 4 pascals (Q) is determined from the pressurization measurements by fitting the equation below, and calculating Q at 4 pascals.

$$Q = K \Delta P^n \qquad (2)$$

where:

Q is the air flow (m^3/hr)
ΔP is the pressure (pascals) and
K and n are constants found from regression of the data.

Errors in calculating effective leakage areas come from several sources; measurement of the pressures across the house and the orifice plate, calibration of the blower door fan, imperfections in the orifice plate and ducting, measuring fan RPM, weather induced pressures, and extrapolation of the data to find the flow at four pascals. We estimate the uncertainity of the calculated leakage areas to be about 10% [8].

The specific leakage area is the ratio of the effective leakage area to the floor area of the building (cm^2/m^2). It allows comparison of the relative leakiness of buildings of different size.

In the Atlanta study, particular attention was given to air loss through the ducts of the central air conditioning/heating system in each house. The houses were tested in three different leakage configurations: with the forced-air distribution fan on, distribution fan off, and with registers and returns sealed. This made it possible to isolate the effect of the forced-air distribution system on infiltration. Infiltration rates were measured in these houses by means of the tracer gas decay technique [9] using sulfur hexafluoride as the tracer gas. All houses were measured with the air conditioning system on, and three were also measured with the vents sealed. During the measurements, the outdoor and indoor wet-and dry-bulb temperatures as well as the wind speed were recorded.

MEASUREMENT RESULTS

Specific leakage and duct leakage measurement results from both the Atlanta and component leakage studies (in Reno and the San Francisco Bay area) are displayed as histograms in Figures 1 and 2. Figure 1 shows the distribution of specific leakage area in the tested houses. The mean value of the specific leakage area is 7.6 cm^2/m^2, however, the distribution is a skewed one with two peaks, one for the component leakage houses and a second for the Atlanta houses. Note that the number of houses represented in Figure 2 does not add up to the total number of houses tested in both studies. This is because not every house was tested for every component: for example, only 21 of the 26 houses in the component leakage study were tested for duct leakage. For those 21 houses, ducts had an average leakage area of 95 cm^2 (13% of the total

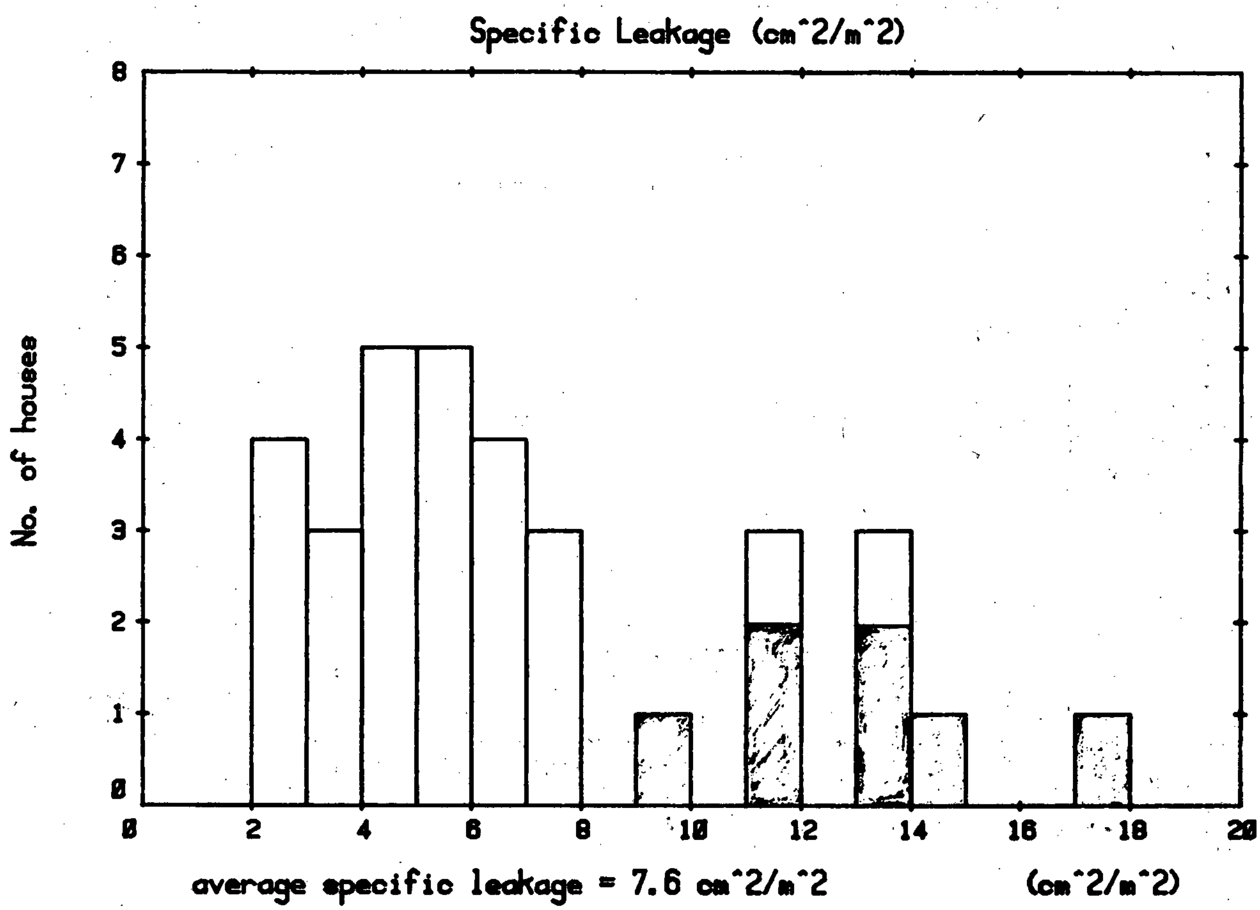


Figure 1: Specific Leakage Areas (cm^2/m^2) for houses tested in component leakage and Atlanta studies. Shaded portions represent Atlanta houses.

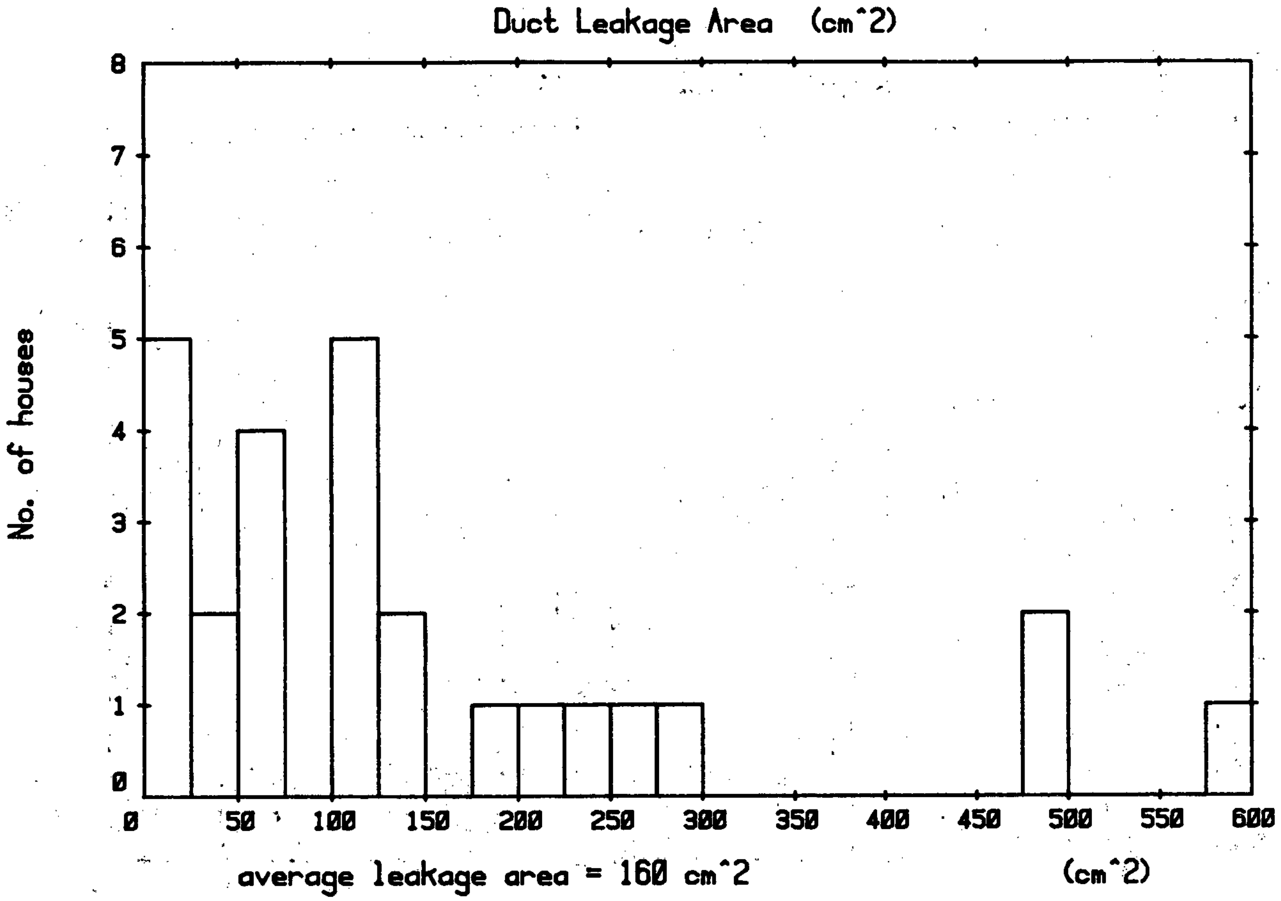


Figure 2: Duct Leakage Area Measurements (cm^2) for houses tested in component leakage and Atlanta studies

leakage area; see Fig. 2). Figures 3 and 4 show the distribution of leakage sites in the houses tested, Figure 3 for houses with fireplace dampers or inserts and Figure 4 for houses lacking a damper.

Table 1 summarizes data from the component leakage study. The results of the Atlanta study are presented in Tables 2 and 3. Table 2 shows the results of the blower door measurements made in the eight houses, while Table 3 presents infiltration rates obtained by single tracer gas decay measurements. These latter quantities are of some interest because they provide a rough indication of the effect of distribution fan operation on the infiltration rate.

DISCUSSION OF RESULTS

Component Leakage Measurements

The twenty-six houses tested in the component leakage study showed a wide range of leakage, as is indicated by their specific leakage, which varied from 2.3 to 13.0 cm^2/m^2. (Tight houses have specific leakages from 2 to 4 cm^2/m^2 and leaky houses range between 8 and 10 cm^2/m^2. A few houses have been found in other studies with specific leakage areas greater than 20 cm^2/m^2.) As seen in the histogram of specific leakage (Fig. 1), the twenty-six houses tested represent an expected distribution of tight to loose houses. The Atlanta houses have an average specific leakage of 13.6 cm^2/m^2, and represent seven of the nine houses with a specific leakage greater than 8 cm^2/m^2.

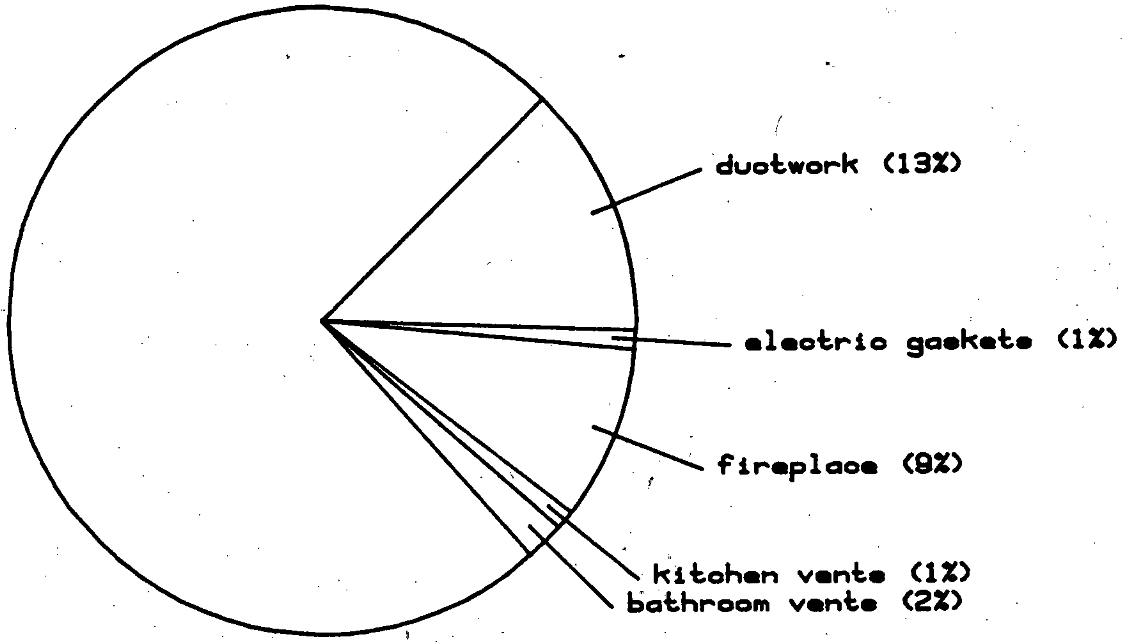
The results from the components studied raise many questions. The average leakage area of the ductwork (95 cm^2, 13% of the total) is in general agreement with other studies. Caffey [10] found duct leakage to be 14% of the total, and other studies done by Lawrence Berkeley Laboratories of energy efficient homes [11,12] found 15% and 21% respectively. Leakage from ductwork is of proportionately greater importance than from any other site, due to the high pressures in the ducts during fan operation. Measurements made in Atlanta (discussed below) suggest that operation of the distribution fan can add .3 to 1 air changes per hour to existing weather-induced infiltration. This type of leakage also results in decreased heating and cooling system efficiency as air is

Table 1. Results of Component Leakage Study

Component	Average leakage area* (cm^2)	% of total leakage area**	No. of houses tested
Ductwork (including plenum)	95 ±25	13 ± 3	21
Electric outlets	8 ±10	1 ±1	12
Kitchen exhaust vent			
(with damper closed)	5 ±2	1 ±0.3	7
(with damper open)	39 ±3	6 ±0.4	12
Bathroom exhaust vent			
(with damper closed)	11 ±1	2 ±0.1	6
(with damper open)	20 ±2	3 ±0.3	9
Fireplace, (without insert)			
(damper closed)	69 ±15	9 ±2	5
(damper open or none)	350 ±30	24 ±4	13
Fireplace, (with insert)			
(with damper closed)	36 ±10	8 ±1	3
(with damper open)	65 ±25	13 ±3	7
Total of components			
for a normal fireplace			
(damper closed)	190 ± 53	26 ±7	5
(damper open)	510 ±70	48 ±9	13
for a fireplace with insert			
(damper closed)	150 ±50	26 ±6	3
(damper open)	230 ±65	37 ±8	7
Total of house (all dampers closed)	800 ±80	100	26

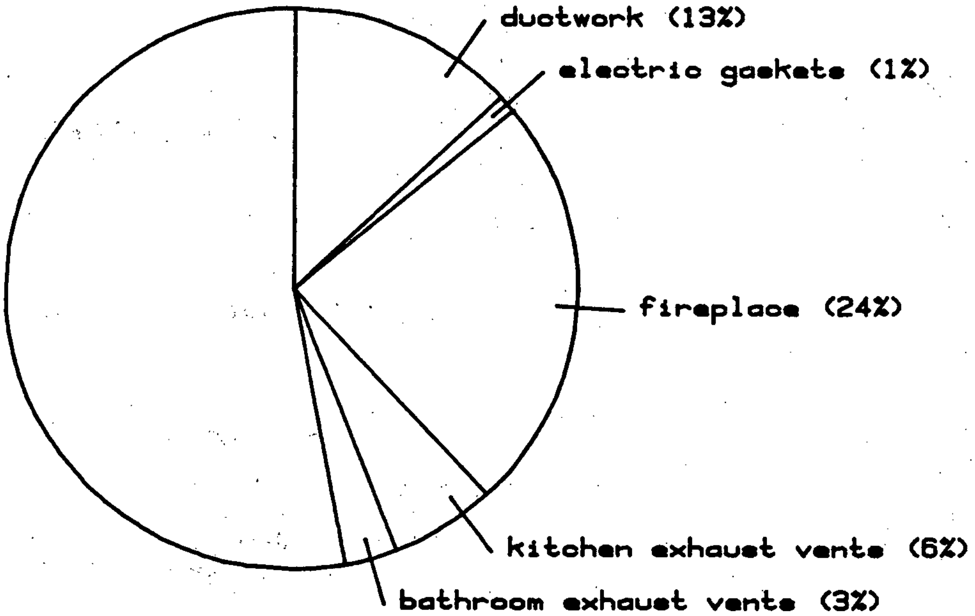
* Uncertainties reflect the method of testing used.

** Percentages based on the subset tested for this component in this leakage configuration.



An average of 26% of the leakage was identified in these homes

Figure 3: Component Leakage Areas for a house WITH dampers



An average of 47% of the leakage
was identified in these homes.

Figure 4: Component Leakage Areas
for a house WITHOUT dampers

lost from the distribution system.

The average leakage of all electrical outlets and switch plates in a house, determined from installation of gaskets behind selected cover plates, was only 8 cm^2 (1 % of total, within the error in the measurements). This is much less than the 20% found in the study by Caffey [13] and suggests that either the housing stock is extremely varied or there is some error in the measurements. (It is possible, of course, that our method of measuring circuit box leakage is inaccurate due to gasket leakage.) On the basis of visual inspection with smoke sticks, it seems unlikely that electrical outlets and switch plates could account for more than 10% of total leakage. In some houses, installation of gaskets actually increased measured leakage areas because the cover plates had previously been sealed with paint.

Kitchen and bathroom exhaust vents were found to have comparable leakage areas: 39 and 20 cm^2, respectively, for kitchen and bathroom vents with no dampers and, 5 and 11 cm^2 for vents with dampers. Dampered kitchen exhaust vents may be tighter than dampered bathroom vents because the grease from cooking aids in sealing. We expected some dampers to be stuck in an open position due to dirt and grease buildup, but this problem was not encountered even though some vents were very greasy. One kitchen exhaust vent tested was of a spring-loaded damper design which sealed completely under normal pressures, yet opened easily during operation of the exhaust fan. Many exhaust vents opened into the attic, a practice that can cause moisture problems. To avoid this, all kitchen and bathroom vents should be exhausted above roof level.

A wide range of fireplace types were encountered during the study. For analysis purposes, these were broken up into two categories: "normal" and "inserts." Inserts varied greatly, from simple glass doors to cast iron wood stove-type inserts. Most had fans to circulate room air around the fire box or through pipes around the fire. The normal fireplace, with the damper closed, had an average leakage area of 69 cm^2 (9% of the total house leakage), which is high for a single leakage site. The average leakage area for an insert with the damper opened and doors closed was 65 cm^2. This suggests that glass doors (or a more complete insert) could be installed in lieu of a damper. The insert might be less expensive and would increase fireplace efficiency [14]. Fireplaces lacking dampers had an average leakage area of 350 cm^2, 24% of total house leakage (including the open fireplace damper). In an average house, opening the fireplace damper increased the leakage area by 46%.

The Atlanta Study

The houses measured in Atlanta all had electric central air conditioning and natural gas heating systems. Return ducts were not insulated, but supply ducts were. In one-story houses, the return and supply ducts were located in the crawlspaces or basements and, in the two-story houses, in the attics as well. All of the houses had partial crawlspaces and either a basement or garage underneath. Crawlspaces were very damp with poor drainage in the claylike soil (plants were growing in one crawlspace). Attics all had blown-in insulation, usually three to five inches of fiberglass. None of the attic hatches were weatherstripped, and few fit well. All exterior doors on older houses were weatherstripped with brass spring metal. The newest homes had doors with vinyl weatherstripping. In only one house was the door to the basement weatherstripped. Windows were usually of double-hung design without weatherstripping and tended to be leaky. Kitchen and bathroom exhaust vents generally lacked anti-draft dampers and several bathroom exhaust vents opened directly into the attic. Fireplace dampers fit well but the joint between the fireplace and the wall was usually poor.

The eight houses were found to be very leaky with specific leakages between 10 and 18 cm^2/m^2 (with the distribution fan off). The leakage areas of the air distribution systems were found by performing measurements with registers sealed and unsealed. They were found to be unusually leaky, accounting for as much as 25% of total leakage area. In a perfectly sealed and balanced air conditioning/heating duct system, one would not expect the distribution fan to change calculated leakage areas. In all the Atlanta houses tested, however, the decrease in effective leakage area from the fan-off to the fan-on condition was of roughly the same magnitude as measured between the "fan-off" condition

Table 2. Effective leakage area, A, (cm^2)
and specific leakage, S, (cm^2/m^2)

house	distribution fan off		distribution fan on		registers and returns sealed		ductwork
no.	A cm^2	S cm^2/m^2	A cm^2	S cm^2/m^2	A cm^2	S cm^2/m^2	A cm^2
1	—	—	2600	13	3000	15	—
2	2500	12	1800	9	1900	9	600
3	2100	18	1600	13	1600	13	500
4	1800	14	1500	12	—	—	—
5	2600	15	1900	11	—	—	—
6	2100	10	1900	9	1900	9	200
7	2300	12	1700	9	1800	9	500
8	2700	14	2500	13	2400	13	300

Table 3. Infiltration measurement data*

house I.D.	distribution fan on or sealed	infiltration rate (ach)	temperature (°C) inside	temperature (°C) outside	wind speed (m/sec)	% relative humidity
1	on	0.29	26.1	30.3	0.0	61
2	—	—	—	—	—	—
3	on	0.67	26.7	33.9	0.0	52
4	on	0.44	24.2	32.2	0.0	80
5	on	0.59	22.8	26.7	1.3	65
6	on sealed	0.60 0.23	24.1	27.8	0.5	65
7	on sealed	0.92 <0.02	28.6	28.3	0.0	50
8	on sealed	0.64 0.41	24.2	22.8	1.0	85

*Data derived from single tracer gas decay measurements in houses.

and "sealed registers and returns". Air leakage at the joints between the house, the plenum and ductwork is common. Infiltration caused by leaks in the ductwork and plenum increased during furnace blower operation because pressures in the ducts and furnace plenum are much greater than the naturally occurring pressures caused by the wind and stack effect. For example, on the basis of a tracer gas measurement, the infiltration rate of house #6 increased from 0.23 ach to 0.60 ach with the distribution blower in operation, even though the effective leakage area of the ducts was 200 cm^2 or only 10% of the total leakage area of the house. Although single tracer gas measurements did not provide completely reliable data on the change in infiltration rates due to blower operation, the tests suggested that much of the air pulled from the house through the return supply duct was lost through leaks in the distribution system.

SUMMARY

The twenty-six houses tested in the component leakage study were found to represent an expected cross section of air tightness. Their average total leakage area was 800 cm^2 with a standard deviation of 380 cm^2, and the average specific leakage was 6.0 cm^2/m^2 with a standard deviation of 3.3 cm^2/m^2 . The biggest leakage sites measured were seen in the ducting of the forced air distribution systems and in fireplaces, which accounted for 13% and 9% of the total leakage area respectively (24% for fireplaces with no dampers). In the average home, leaving the fireplace damper open will increase the leakage area by 37%. Installation of electric switch plate and receptacle gaskets appeared to stop about 80% of the leakage through these sites judging by smoke sticks yet this accounted for only 1% of the total leakage area. Kitchen and bathroom exhaust vents were similar representing 1% and 2% respectively of the total leakage for vents with dampers and 6% and 3% for vents without dampers. An average total of 26% of the house leakage area was found in the measured components, 48% for houses with no fireplace dampers and 37% for houses with fireplace inserts and dampers open. It seems likely that the remaining leakage is located in the building structure, for example, at joints between walls, floors and ceiling, around plumbing penetrations and so on.

The houses measured in Atlanta were found to be quite leaky by comparison with the normal distribution of leakage areas. This condition may be attributed to the generally loose construction that typifies building practices in mild climates such as that which Atlanta enjoys. Architectural styles in mild climates tend toward large window areas and numerous doors—both common leakage sites. It seems likely that, in these houses, doors and windows account for a greater fraction of total leakage area than the customary 25%. Heating and cooling ducts were found to account for a large fraction of the leakage in these houses: an average of 16%, with a maximum of 25%. Operation of the blower could increase infiltration rates by as much as 50% as a result of leaks within the ductwork. It appears that sealing the ducts could provide an inexpensive and easy means of reducing air leakage to unconditioned spaces.

The number of measurements made of individual components was not great, and it would be useful to test more houses in other regions of the country and of varying construction types and ages. There are many leakage sites yet to be measured, such as plumbing penetrations and baseboards, that do not lend themselves to the component testing procedure used in this study. The method of pressurizing the entire house and sealing selected components in order to measure their leakage has been used in other studies, but is quite awkward [15]. Of course, extensive measurement of a home causes great inconvenience to the homeowner, one of the biggest drawbacks to complete testing. In the end, the homeowner (or house operator) has a great deal of control over the leakage area and therefore, the infiltration rate of the house.

The studies described in this paper found that measured components account for 26 to 47% of the leakage area in a house. We generally assume that a certain percentage reduction in leakage area (for example, 30%) results roughly in a like reduction in infiltration. If infiltration accounts for 25 to 50% of energy use in a building, the consequent reduction in energy consumption due to leakage area reduction will be on the order of 7.5 to 15%. Knowledge of building components with large leakage areas will make it possible to structure weatherization programs so as to maximize reductions in leakage area and consequent energy savings.

ACKNOWLEDGMENTS

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720