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Infiltration Measurement and Control in the Context of an Energy Audit

D.T. GRIMSRUD, R.C. SONDEREGGER and M.H. SHERMAN

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Summary

An energy audit is being developed at Lawrence Berkeley Laboratory to determine economically optimal retrofits for residential buildings, based on actual, on-site measurements of key indices of the house. Measurements are analyzed on a microprocessor and retrofit combinations compatible with minimum life-cycle cost and occupant preferences are then determined. A particularly important element of this audit is its treatment of infiltration. A measurement of the effective leakage area of the house using fan pressurization is combined with weather data and local terrain information to predict average infiltration using a model developed at LBL. "House-doctoring" of the largest leakage sites during the audit reduces the leakage area approximately 25%.

Introduction

Energy conservation in buildings has been and will continue to be an important issue in the United States. The building sector alone accounts for a third of national energy consumption. While an obvious response to this situation is change in construction practices that will lead to more energy efficiency in buildings, the time scale of the change will be long. Already, 80% of the 1990 housing stock in the United States has been built.

Audit and retrofit programs, designed to improve the condition of existing buildings, are beginning in several areas of the country. This paper describes a residential audit procedure that uses field measurements to assess the current condition of a house. The information obtained in the measurement becomes an input to a microprocessor to compute the house's energy load. After calculating the energy load, the microprocessor examines a list of retrofits that can be applied to this structure and produces a rank-ordered retrofit list, arranged by cost effectiveness.

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This paper describes the audit procedure and examines in detail the problem of measuring and controlling a particularly significant portion of the energy load in houses, that due to infiltration.

The Microprocessor-based Energy Audit

Before the actual audit visit, past utility bills of the house and weather data are screened to obtain an "energy signature" for the house. Subsequently, two auditors visit the house. They note window types and measure dimensions, test the envelope for leakage with a blower door that pressurizes or depressurizes the house, identify leaks, plug the easy ones as they go and note the ones that are more difficult to repair. While one auditor measures furnace efficiency, checks water and air temperature settings, and estimates envelope R-values, the other auditor repairs air leaks, installs water heater insulation, changes the furnace air filter, calibrates the thermostat and, with the permission of the homeowner, installs a low-flow showerhead and resets the water heater thermostat.

At the conclusion of the physical inspection, all necessary data are collected and fed to the microprocessor. The microprocessor features a state-of-the-art interactive program that asks simple questions and provides further information on its questions when requested. The homeowner is present during this process and is encouraged to answer the questions either directly, or through the auditors. The auditors then help the homeowner decide on a suitable retrofit package. The program scans a master list of possible retrofits stored on a disk that includes conservation measures, such as insulation, storm and double-pane windows, insulating shutters, caulking and weatherstripping, vent dampers, replacement burners, and active and passive solar retrofits for space and water heating.

There is ample occasion for interaction between the homeowner and the program to insure that no optimized retrofit lists are produced with items unacceptable to the homeowner, and that the homeowner is educated on-site about the costs and benefits of retrofits. Of course, our cost estimates of all retrofit packages acknowledge that homeowners may do some retrofits themselves and hire a contractor to do others. At the conclusion of the visit, the auditor leaves behind specific detail information on the suggested retrofits.

A dynamic heating and cooling load model with algorithms to calculate internal heat gains and solar gains is used to evaluate fuel savings.

Infiltration

Infiltration, the uncontrolled leakage of air into a house, is a sizeable fraction of the energy load of the structure. Several standard techniques exist to measure infiltration in a building. However, few of the standard techniques are applicable for an energy audit because of the limitations in time inherent to an audit. The time constraint forces us to adopt either a short, cursory examination of the structure to give information about infiltration or to use a less direct measurement procedure using fan pressurization. The simplicity and speed of the latter technique and the quality of the infiltration predictions obtainable with it are the impetus to use this procedure in the audit. Fan pressurization has been described in several publications [1-3]; consequently our description shall concentrate on features unique to our measurement procedure.

A fan mounted on an adjustable wooden plate is sealed into a doorway of a house to be tested. The fan speed, which can be adjusted using a DC motor and controller, is varied to produce a pressure drop, ΔP, across the building envelope. The flow through the fan required to produce this pressure difference is determined and the process repeated for fixed pressure increments to produce a curve relating the pressure drop across the envelope to the flow required to produce it. The fan direction is reversed and a corresponding curve of depressurization versus flow is obtained in the same manner.

The flows at equal positive and negative pressures are averaged. In the pressure region used ($\pm$ 10 to $\pm$ 60 Pa) the data generally form a straight line on a log-log plot, i.e., the data are well represented by the empirical relationship

$$Q = K\,\Delta P^{n} \qquad (1)$$

where: Q is the volume flow rate of the fan [m^3/s],

K is a constant,

ΔP is the absolute value of the pressure drop across the building envelope [Pa] , and

n is an exponent in the range $0.5 < n < 1.0$.

The curve is then extrapolated toward the low pressure end of the graph to determine the flow at 4 Pa. A particular flow model is now invoked to compute the effective leakage area (ELA) of the structure. An assumption is made that in the low pressure regime in the vicinity of 4 Pa (a pressure of this order is typical of the pressures that drive natural infiltration) the pressure-flow relationship has the form of inviscid flow through large openings, i.e.

$$Q = A\sqrt{\frac{2}{\rho}\Delta P} \qquad \text{for } \Delta P \simeq 4 \text{ Pa} \qquad (2)$$

where: A is the effective leakage area [m^2], and

ρ is the density of air [kg/m^3].

This expression, in turn, is used to compute the effective leakage area.

Our choice of the form of the flow relationship given in Eq. (2) is the result of measurements of the leakage of a house at very low pressures using a technique we call AC pressurization [4]. These measurements show that even at pressures as low as a few tenths of a pascal the flow characteristic for the houses tested was typical of the flow through an orifice (inviscid flow) rather than flow through narrow cracks dominated by viscous interactions with the walls.

A model relating the effective leakage area measured with fan pressurization to the infiltration experienced in various weather conditions has been developed at Lawrence Berkeley Laboratory [5]. The model is the key element that allows the inclusion of fan pressurization measurements in an energy audit to predict infiltration values. Briefly, the model combines the effective leakage area, A, with parameters associated with the house and the local weather conditions to predict the infiltration, Q.

$$Q = A\left[f_s^2\,\Delta T + f_w^2\,v^2\right]^{1/2} \qquad (3)$$

where: Q is the infiltration [m^3/s],
A is the effective leakage area [m^2],
ΔT is the average indoor-outdoor temperature difference [K],
f_s is called the reduced stack parameter [$m/s/K^{1/2}$],
v is the average wind speed at the house, and
f_w is the reduced wind parameter.

This expression displays the inherent simplicity of the model. The infiltration is the product of terms that depend only on the structure of the house and its surrounding terrain (A, f_w, f_s) and weather-dependent terms (ΔT, v). Once f_w, f_s and the effective leakage area are determined, the average infiltration for any particular time interval is found by determining the average values of ΔT and v for that interval and combining using Eq. (3). Thus the house parameters are determined but once, while infiltration values for various time intervals can be found by using the average weather variables over these intervals in Eq. (3).

The terms f_s and f_w are complex expressions but their interpretation is straightforward. We must first introduce two additional expressions. The fraction of the total leakage that is horizontal (i.e., the sum of the floor and ceiling leakage areas divided by the total) is called R.

$$R = \frac{A_c + A_f}{A} \qquad (4)$$

The fractional difference between the ceiling leakage area, A_c, and floor leakage area, A_f, is called X.

$$X = \frac{A_c - A_f}{A} \qquad (5)$$

The stack parameter is expressed in terms of X, R, the acceleration of gravity, g, the absolute temperature, T, and the height of the ceiling above grade, H_h, as:

$$f_s = \frac{1}{3}\left(1 + \frac{R}{2}\right)\left[1 - \frac{X^2}{(2 - R)^2}\right]^{3/2}\left(\frac{gH_h}{T}\right)^{1/2} \qquad (6)$$

The wind pressures on the surface of the house depend upon the terrain class and the shielding class of the structure. The terrain class is affected by the large-scale obstructions in the several square km region of the house. The shielding class is determined by trees, fences and other buildings located in the immediate vicinity of the house.

The wind speed at a measurement site in the region is first corrected to a speed at a standard height using the terrain class at the measurement site, then is adjusted back to the wind speed at the height of the house using the terrain class of the house. Combining all the terms we have:

$$f_w = C'(1 - R)^{1/3}\left[\frac{\alpha_h (H_h/10)^{\gamma_h}}{\alpha_m (H_m/10)^{\gamma_m}}\right] \qquad (7)$$

where: C' is the shielding coefficient for the house site,
R is the fractional horizontal leakage area,
α_h, γ_h are the terrain class constants for the house,
H is the height of the house [m],
α_m, γ_m are the terrain class constants for the wind measurement site, and
H_m is the height of the wind measurement [m].

The values of α and γ for standard terrain classes are presented in Table 1, below.

Table 1: Terrain parameters for standard terrain classes

Class	γ	α	Description
I	0.10	1.30	Ocean or other body of water with at least 5 km of unrestricted expanse
II	0.15	1.00	Flat terrain with some isolated obstacles (e.g. buildings or trees well separated from each other
III	0.20	0.85	Rural areas with low buildings, trees, etc.
IV	0.25	0.67	Urban, industrial or forest areas
V	0.35	0.47	Center of large city

Most airport wind-speed measurements are made in terrain class II while most houses are found in terrain classes III and IV. The generalized shielding coefficients are presented in Table 2, below.

Table 2: Generalized shielding coefficient vs. local shielding

Shielding Class	C′	Description
I	0.324	No obstructions (trees, fences, nearby houses) whatsoever
II	0.285	Light local shielding with few obstructions
III	0.240	Some obstructions within two house heights
IV	0.185	Obstructions around most of perimeter
V	0.102	Large obstruction surrounding perimeter within two house heights

An example of the ability of the model to predict infiltration on a short term basis is shown in Fig. 1. Here, we use a three-day data set recently measured by our Mobile Infiltration Test Unit (MITU), a trailer outfitted with adjustable leaks and cracks, pressure sensors and weather station used for detailed field investigations of air infiltration phenomena. The solid line shows infiltration measurements obtained using a controlled flow injection system [6] at half-hour intervals over the three-day period shown. The dotted line represents the infiltration predicted for this structure using Eq. (3). The average measured infiltration for this structure over the period shown is 26.7 m^3/hr. The average computed from Eq. (3) for the interval is 28.5 m^3/hr.

The Problem of Retrofits

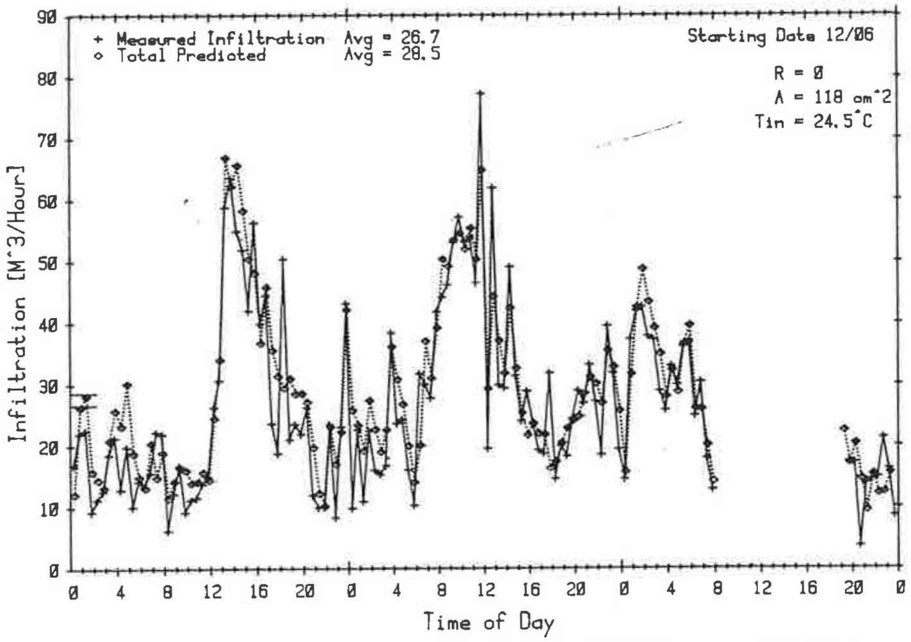

Fig 1. AIR INFILTRATION vs TIME

The list of retrofit options available is long. Once again, the results of the model are instructive. They predict that on average, the change in the infiltration of the structure is proportional to the change in the total leakage area. Unfortunately, field measurements of the leakage area of various building components or the changes in leakage area associated with various retrofit procedures are limited. However, there are some useful constraints that can be employed to estimate quickly the importance of various leakage sites.

The total leakage area of many houses in the United States and Canada has been measured in several different studies [7-9]. We have found it useful to use the concept of specific leakage area (SLA) to group data. The SLA is defined as the ratio of the effective leakage area of a house measured in centimeters squared to the house's floor area measured in units of meters squared. In these units, the SLA of houses we have measured are found in the convenient numerical range of 1 to 20 [cm^2/m^2]. Differences in the ELA of similar houses due solely to variations in the size of the house should be removed by using the concept of SLA. Fig. 2 shows box plots* of the SLA of several groups of houses measured recently. Clearly, the component leakage values we are interested

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* A box plot, a useful way to represent a large group of data, was introduced by Tukey [10]. The two extreme values of the data are represented by circles, the extremes of the box represent the values separating the first and second quartiles, and the third and fourth quartiles; while the line through the center of the box represents the median value to the data set.

in determining must be consistent with the total leakage areas measured in the studies referred to above.

An example to the reduction in leakage area that may be obtained by patching major leakage sites in the course of a careful audit is presented in the box plot shown in Fig. 3. This plot shows the reduction in total leakage area obtained by two auditors working in large single-family residences in Walnut Creek, CA for a single day.

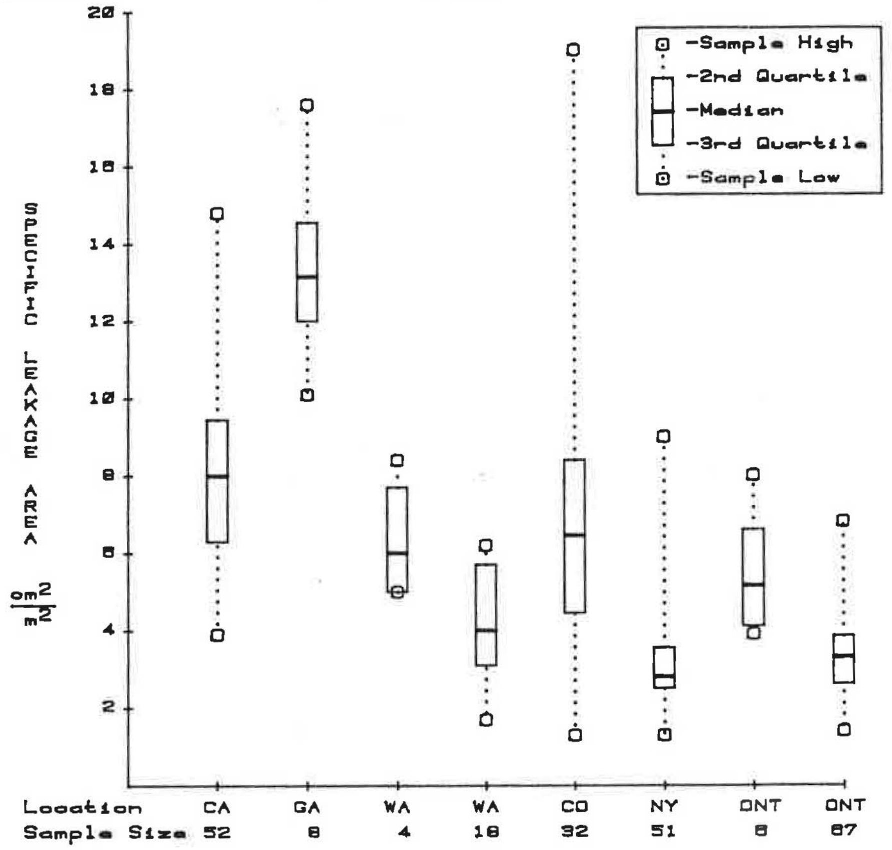

FIG. 2: SPECIFIC LEAKAGE AREA MEASUREMENTS IN NORTH AMERICA

Fig. 3 shows that the median SLA decreased from 8.6 to 6.0 cm^2/m^2, a reduction of 29%. The minimum change obtained in the 16-house sample was 14%, the maximum, 65%.

An example illustrating the lack of effectiveness of a standard "add insulation and storm windows" retrofit in reducing air infiltration is shown in Fig. 4 [8]. The left box of each set is the mid-quartile range of the specific leakage area before retrofit; the right gives results nine months later measured after retrofit. Group 1 was a control group; Group 2 received only attic insulation while Group 3 received attic insulation, crawl-space insulation and storm windows.

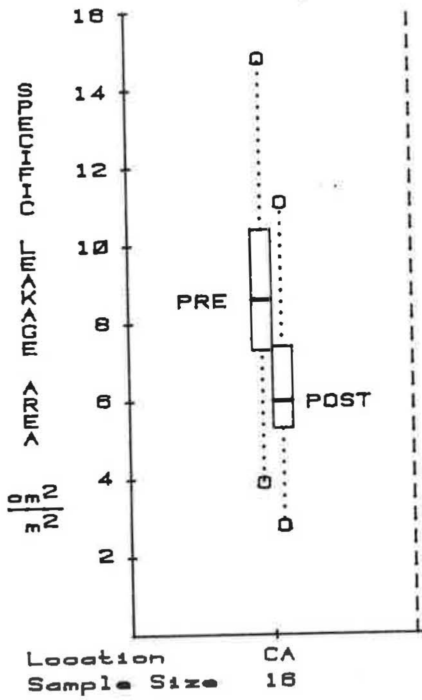

FIG. 3: WALNUT CREEK RETROFIT

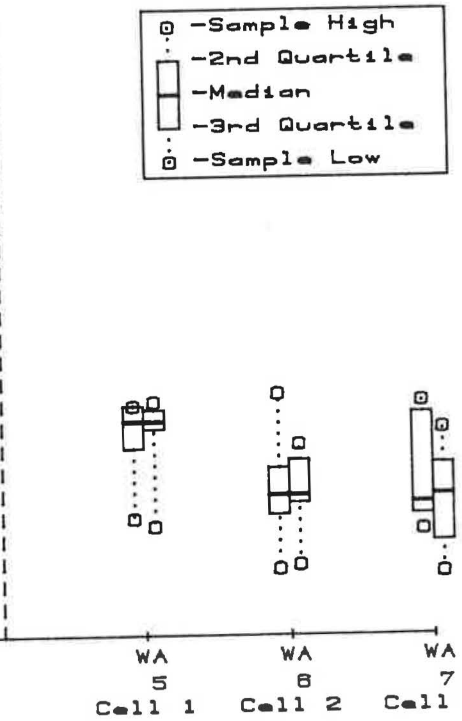

FIG. 4: BPA RETROFIT PHASE 1

In no case shown in Fig. 4 did the median SLA of a group decrease. Preliminary sampling of energy use after the retrofits showed 13% reduction for group 2 and 29% reduction in group 3. A second phase of the project includes retrofits to reduce air leakage and installation of air-to-air heat exchangers to assure adequate ventilation.

Conclusions

To summarize, infiltration measurements in the context of an instrumented energy audit can be made quickly and accurately by using the fan pressurization technique. The measurement provides a value of the effective leakage area of the structure. In addition, particular leakage sites can easily be identified by using smoke sticks or other air flow pattern detectors. The technique is direct, uses simple equipment and provides measurement values that can be analyzed simply in the field to find the infiltration.

We have approached the question of the reduction in leakage area and infiltration and the consequent reduction in energy load of the structure as though its acceptability is obvious. However, reducing infiltration in houses reduces the effectiveness of the most common mechanism used to control indoor air pollution. The topic of measurement of indoor air quality and strategies that can be employed to assure adequate indoor air quality while minimizing energy use will be addressed in several other papers at this conference.

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