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Air Infiltration in Low-Rise Residential Buildings:

State-of-the-Art Review

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TABLE OF CONTENTS

Section Page

1.0 INTRODUCTION 1

2.0 RESIDENTIAL AIR INFILTRATION MEASUREMENT TECHNIQUE. . 9
2.1 Measurement Techniques for Determining the Rate of Air Infiltration Directly. 10
2.2 Measurement Techniques for Determining Leakage. . . . 20
2.3 Additional Measurement Equipment and Physical Information Necessary for the Determination of Air Infiltration or Leakage 31
2.4 Summary of Measurement Techniques 35

3.0 RESIDENTIAL AIR INFILTRATION CASE STUDIES 37
3.1 Case Studies Involving the Measurement of Infiltration Directly 38
3.2 Case Studies Involving the Measurement of Air Leakage 48
3.3 Case Studies Concerning Both Infiltration and Leakage 55

4.0 TECHNIQUES FOR DETECTING AND REDUCING AIR INFILTRATION IN NEW AND EXISTING HOUSES 60
4.1 Methods for Detecting Air Infiltration. 61
4.2 Methods for Reducing Air Infiltration in Existing Houses 66
4.3 Design and Construction Details for Reducing Residential Air Infiltration. 70

5.0 OCCUPANT EFFECTS ON AIR CHANGE RATES. 81

6.0 INDOOR AIR QUALITY AND INFILTRATION 94
6.1 Typical Indoor Air Pollutants 95
6.2 Controlled Ventilation. 109

APPENDIX A: References. 112

APPENDIX B: Lawrence Berkeley Laboratories Air Infiltration Bibliography 125

1.0 INTRODUCTION

This report is a review of current and past air infiltration research related to low-rise residential structures. Several hundred papers have been reviewed and numerous researchers contacted during the preparation of this report. Low-rise residential infiltration projects have constituted the majority of air infiltration research over the last few decades; only in recent years has the research expanded to include high-rise apartments, commercial, and industrial building. Some of the research of larger structures has also been reviewed but is not presented here.

The following five subject catagories emerged from the literature review as the major topical areas.

1. Air infiltration and leakage measurement techniques
2. Case studies measuring infiltration and leakage
3. Air infiltration detection techniques plus construction and retrofit methods to reduce infiltration
4. Occupant effects on the total air-change rate
5. Indoor air quality as affected by infiltration

The literature relevant to each of these catagories is discussed at length in Chapters 2 through 6. Two appendices are also included in this report; Appendix A includes the specific references noted in the text; and Appendix B. is an air infiltration bibliography.

The Energy and Environment Division of the Lawrence Berkeley Laboratories (LBL) and the Air Infiltration Center for the International Energy Agency (IEA) hav developed on-line computer bibliography search capabilities. LBL supplied Technology + Economics, Inc.

with a complete listing of their air infiltration data base; this is presented in Appendix B. The IEA data is planned to be operational by April 1980 and will include international listings, while the LBL data base is confined to North American research efforts. In the near future both of these organizations intend to expand their bibliographic data bases by adding actual infiltration measurement data.

The research papers reviewed represent the work done in a number of countries over the past several years. As a result, the terminology and nomenclature varied widely from paper to paper. Therefore, the definitions and nomenclature used throughout this report are presented in Tables 1-1 and 1-2 respectively. The definitions and nomenclature are based on a recent IEA report (DOE 1979).* Furthermore, wherever possible quantities and equations are expressed in metric units. However, this was not possible in every case; these exceptions are noted in the text. Table 1-3 presents some helpful relationships between SI and English units. Before proceeding to the detailed discussions presented in the remaining chapters of this report, it is useful to consider the magnitude of the infiltration problem and briefly review the physical forces driving infiltration.

The actual magnitude of infiltration is a function of the prevailing weather conditions (e.g., wind velocity, inside-outside temperature difference, humidity, etc.), building integrity, occupant behavior, and the surrounding terrain. It is generally estimated that 30-40 percent of the heating energy used in a typical low-rise residential structure can be attributed to infiltration. Thus if the energ

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*Reference to specific reports are indicated by the principal author and year of publication. Complete bibliographic information can be found in either Appendix A or B.

Table 1-1

Air Infiltration Definitions

Infiltration; is the leakage of air through the building envelope due to imperfections in the structure and therefore, cannot be controlled by the occupant.

Ventilation, is the air flow resulting from specific design provisions which connect the inside with the outside (e.g. operable windows, and exhaust fans). Ventilation is controlled directly by the occupant.

Mechanical Ventilation, is the air required for safe and efficient operation of the heating and air conditioning systems. The amount of air controllably introduced into the structure depends on the size and type of mechanical equipment and the prevailing weather conditions.

Stack effect, is the phenonenon related to the buoyancy of air which creates a pressure differential across the building envelope due to the temperature difference between inside and outside air.

Wind effect, is the phenonenon related to the pressure distribution imposed on the building envelope due to the movement of air around and over the structure.

Table 1-2

Air Infiltration Nomenclature

C	Concentration of tracer gas in the ventilated space at time t
C_i	Initial concentration of tracer gas at time = 0
C_o	Concentration of tracer gas in the outside air
C_T	Total equivalent crack length
G	Net rate of generation of tracer gas in the ventilated space
h	Height of the neutral zone
INF	The level of infiltration in air-changes per unit time
INF_w	Infiltration due to wind
INF_t	Infiltration due to temperature difference
K	Flow coefficient
n	Flow exponent (n and m are used in Chapter 3 to represent the number of window vent and casement window openings.)
P	Free wind velocity head or atmospheric pressure
ΔP_T	Inside-outside pressure difference due to temperature difference
ΔP_W	Inside-outside pressure difference due to the wind
t	Time
T_o	Outside air temperature
T_i	Inside air temperature
V	Volume of the ventilated space
$\dot{v}$	The rate at which air leaves the ventilated space in volume per unit time or the rate at which air enters the ventilated space normalized to inside temperature
W	Wind speed
β_o	Regression coefficient discribing the construction quality of the dwelling

In addition to the above symbols, numerous constants appear throughout report in the form A, B, C, D, E, F, etc.

Table 1-3

Conversion Chart

Physical Quantity	To Convert From	To	Multiply by:
Length	km	mile	0.62
Length	m	ft.	3.28
Length	m	in.	39.37
Area	m^2	$ft.^2$	10.76
Area	m^2	in ~~ft.~~^{2}	1549.40 ?
Volume	m^3	$ft.^3$	35.34
Pressure	Pa	in Water	4.02×10^{-3}
Pressure	Pa	$lb._f/in.^2$	1.45×10^{-3}
Velocity	m/s	miles/hr.	2.24
Flow rate	m^3/s	$ft.^3$/min.	2118.60
Power	W	Btu/hr.	3.41
Energy	J	Btu	9.48×10^{-4}
Temperature	^oC	^oF	$1.8\ ^oC + 32$

consumed in the United States in 1980 equals 84.4 x 10^{20} J (80 Quads) and if the residential heating energy use sector uses approximately 15% of this total then the amount of energy associated with infiltration equals 3.8-5.0 x 10^{20} J (3.6-4.8 Quads) or about 4.5-6.0 percent of the total.

This exchange of air has the benefit that it maintains a safe and healthy environment for the occupants, and maintains the integrity of the structure by removing moisture and preventing condensation damage. However, the rate of infiltration found in typical dwellings far exceeds what is needed for these purposes. Several researchers, architects, and home builders believe that the level of infiltration can be reduced by 60 percent in existing houses without affecting the health and safety of the occupants. If the full magnitude of these savings were realized in a single year then the energy savings would amount to approximately 2.3-3.0 x 10^{20} J (2.2-2.9 Quads) or the equivalent of saving 1.06-1.40 million barrels of oil per day. This represents a 2.7-3.5 percent savings nation-wide. These estimates are based on the existing housing stock; future residential construction can achieve even greater savings.

Two important natural phenomena which drive infiltration are wind pressure and inside-outside temperature difference (stack effect). The force exerted on the structure as a result of wind and stack effects causes an imbalance in the absolute levels of inside and outside pressure. Therefore, depending on the leakiness of the envelope varying amounts of air will be exchanged between the inside and outside environments. A further effect arises from operation of fossil fuel heating systems. Fossil fuel heating systems require large volumes of air for combustion and for removal of the exhaust gases up the stack. Unless positive means are provided for introducing this air directly from the outdoors, it will be drawn from inside the structure, contributing substantially to the infiltration load.

When the wind blows past a structure, the windward side will experience an increase in static pressure. The pressure imposed on the envelope ranges between 0.5 and 0.9 of the free wind velocity head. On the leeward side, negative pressures exerted on the structure are between -0.3 and -0.6 of the free-wind velocity head. ASHRAE (1977) suggests that the free-wind velocity head can be calculated using the following relationship:

$$P = 0.000482 \times W^2$$

where

P = velocity head, inches of water

W = wind velocity, miles per hour

Furthermore, the configuration of the roof also affects the surface pressures; for instance, a slightly pitched roof will generally experience a negative pressure, while a steep pitched roof will experience positive surface pressures.

When looked at in more detail, the interaction between the wind and the structure becomes very complex. As pointed out by DOE (1979) "the pressure differences due to wind varies over the surface of the building at every point, depending on the wind speed, [wind] direction, building height, internal pressure, crack distribution and size..." Furthermore, the dynamic or pulsating nature of the wind adds further complexity to the situation. Recent researchers have speculated that even at relatively low wind speeds, local fluctuations in the magnitude and direction of the wind may cause measurable infiltration.

Further research is needed in this area to better understand the response of a structure to low velocity, pulsating winds.

The difference between inside and outside temperatures causes a gradient in air densities. If the inside temperature is greater than outside, then the difference in densities causes a negative pressure across the lower portion of the envelope and thus forcing air to flow into the structure. This movement of air into the structure near the ground is accompanied by the outflow of air at the top thus maintaining continuity of flow. With air entering at the lower portion of the structure and leaving at the upper levels, there exists a horizontal plane where the pressure difference due to temperature is zero, and thus the net air flow also equals zero. This plane is defined as the neutral zone. The location of the neutral zone is a function of the location of cracks, windows, and doors in the walls as well as openings inside the structure.

In addition to wind and temperature effects on infiltration, the operation of the heating system, exhaust vents, windows, and doors all affect the total amount of air entering or leaving the structure. Most of the research projects reviewed deal with the wind, temperature, heating system operation; very few discuss the impact of occupant behavior on the movement of air through the structure.

2.0 RESIDENTIAL AIR INFILTRATION MEASUREMENT TECHNIQUE

Over the past 30 years numerous measurement techniques have been employed by a multitude of researchers. The review of current and past research efforts indicate that the measurement of air infiltration falls into the following two categories:

- measurement of actual infiltration
- measurement of induced leakage

Direct measurement of actual air infiltration can be accomplished by injecting a gaseous substance into the air and observing the variation of the concentration over time. This method is referred to as the tracer gas technique. Sometimes radioactive elements (radon, kryton, etc.) are used as tracers; however, most researchers have chosen a gas not found in the indoor/outdoor environment in large quantities (e.g. hydrogen, helium, carbon monoxide, sulfur hexafluoride, etc.). Since air infiltration is a function of several physical phenomena (wind velocity, indoor-outdoor temperature difference, house type, orientation, etc.) the tracer gas technique must be applied over a broad range of weather conditions and house types before conclusions about the functional relationship can be drawn. Therefore, some researchers have made use of a second measurement technique: the pressurization method. This method requires determination of the rate of air leakage as a function of pressure. The principal objective of this approach is to characterize the structure; therefore, the imposed pressure is generally much greater than the pressure developed by the physical phenomena. This fact makes the relationship between the tracer gas approach and the pressurization approach very complex. Furthermore, other approaches exist which are useful for locating areas of structure that leak but are less quantifiable. These measurement approaches will be discussed in detail in the first two sections of this chapter.

In addition to these measurement techniques a number of other parameters must be measured during the course of the air infiltration test or quantified during a physical inspection of the structure. These parameters include the surface pressure on the exterior of the structure, indoor and outdoor temperatures, indoor and outdoor humidity levels, wind direction and speed, and many others. The various types of equipment used to measure these items and the type of physical inspection required will be discussed in the third section of this chapter.

Since these measurement techniques are of such great importance in assessing air infiltration, each method will be carefully examined. The advantages and disadvantages of each method will be summarized. Also, the measurement procedures preferred by various researchers will be presented where appropriate.

2.1 Measurement Techniques for Determining the Rate of Air Infiltration Directly

The principal means for determining the level of infiltration in a residential structure is through the use of a tracer gas. One way to perform this technique is to make a one-time injection of the tracer gas into the indoor environment and then simply measure the decrease in the concentration as a function of time. This is known as the decay method or tracer dilution method. The second major approach involves the continuous (or semi-continuous) injection of the tracer gas into the indoor air while monitoring the rate of injection and concentration of the tracer gas.

The equations which govern these two approaches will be presented first. Then the various tracer gas and specific measurement equipment which have been used will be discussed. This discussion will highlight some of the recent research which compared the level of infiltration as determined by various tracer gases. In general, the comparison indicates that the differences in the level of infiltration are not significantly greater than the experimental measurement error. Thus, although the physical properties of the tracer gases vary widely, these differences are not responsible for the different levels of infiltration measured; indeed the difference may be more closely related to the type of equipment used to measure the concentration of the tracer gas.

The rate change in the concentration of a particular gas or element in the indoor air is equal to the difference between the outdoor and indoor concentrations times the rate at which air is being exchanged plus a generation term which is a measure of the rate at which the substance is being produced or injected. Thus, the rate change equation consists of a sink and source term and can be expressed by the following differential equation:

$$V \frac{dc}{dt} = (C_o - C)\,\dot{v} + G \tag{2.1}$$

where

V = the volume of the ventilated space
C_o = the concentration of the tracer gas in the outside air
C = the concentration of the tracer gas at time t
$\dot{v}$ = the rate at which air leaves or enters the structure
G = the net rate of generation of the tracer gas with the structure
t = time

Consider first the tracer gas decay method--the generation term (G) equals zero and if the tracer gas is not present in the outdoor air then C_o equals zero as well. Thus equation 2.1 reduces to:

$$V \frac{dc}{dt} = - C \dot{v} \qquad (2.2)$$

which can be solved to yield

$$\ln \frac{C_2}{C_1} = \frac{\dot{v}}{V} (t_2 - t_1) = -INF(t_2 - t_1) \qquad (2.3)$$

where C_1 is the concentration of gas at t_1 and C_2 is the concentration at t_2. The quantity $\dot{v}/V$ is by definition the level of infiltration (INF) and has units of air changes per unit time. By plotting the concentration versus time on semi-log paper the level of infiltration will equal the slope of the line. In using this approach the infiltration rate is automatically normalized to the inside temperature. Equation 2.3 is often expressed in exponential form as follows:

$$C_2 = C_1 \, e^{- INF\ t} \qquad (2.4)$$

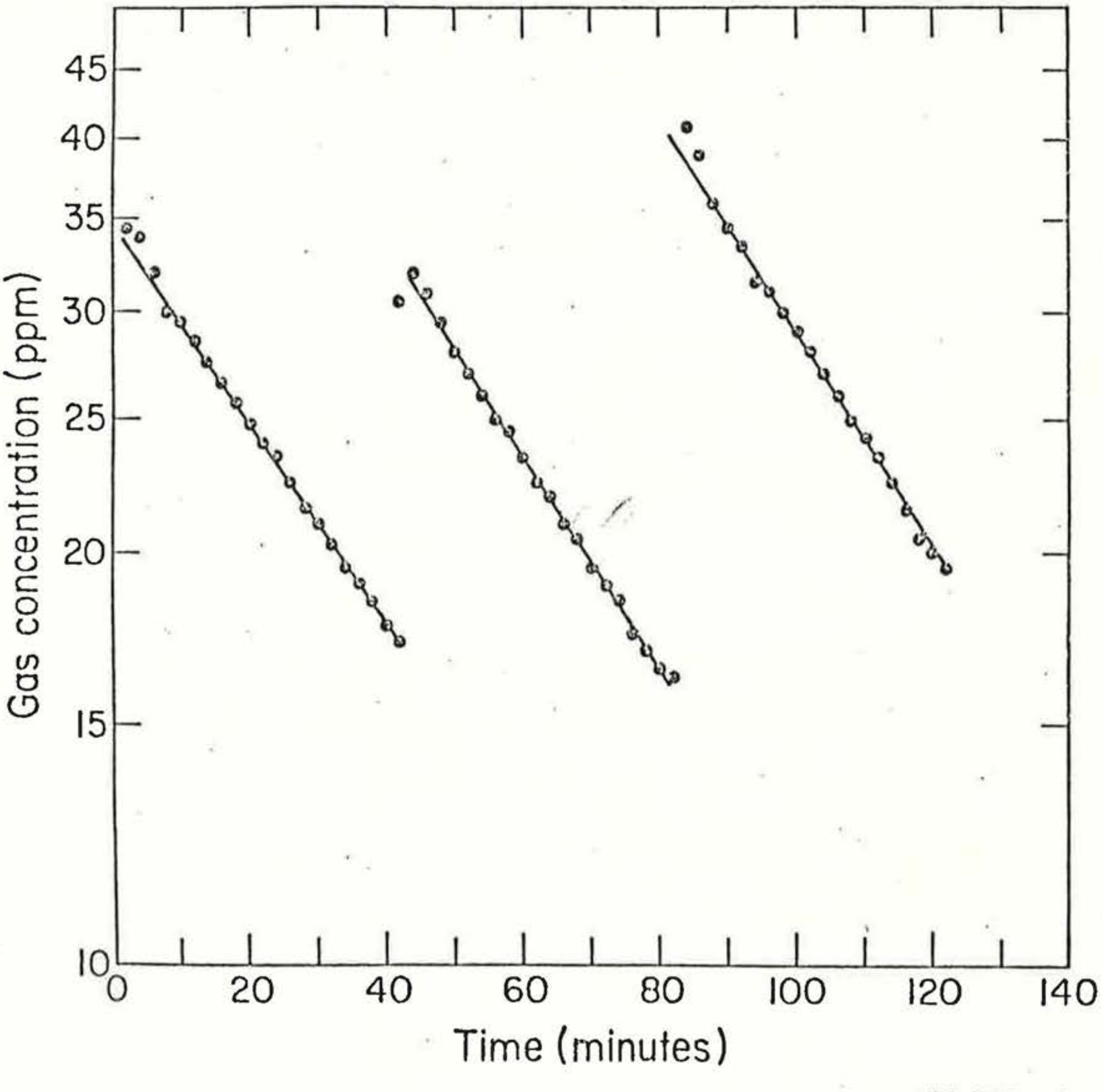
Figure 2-1 shows typical plots of infiltration using the decay approach. In this study by Condon et al., (1978) they injected the tracer gas at 45 minute intervals and monitored the concentration during the intervening period.

The second approach for measuring the infiltration rate is also based on the basis rate equation 2.1. However, in this case the source term (G) is not zero but some fixed value. Assuming once again that the outdoor concentration of the tracer gas is negligible, then equation 2.1 becomes:

$$V \frac{dc}{dt} = -C \dot{v} + G \qquad (2.5)$$

Figure 2-1

Typical Infiltration Plot Using the Tracer Gas Decay Method



XBL 783-459

Source: Condon (1978)

which can be solved to yield:

$$\ln\left(1 - \frac{C}{G}\dot{v}\right) = -\frac{\dot{v}}{V}t = -\text{INF}\ t \qquad (2.6)$$

or the exponential form:

$$C = \frac{G}{\dot{v}}\left(1-e^{-\text{INF}\ t}\right) \qquad (2.7)$$

Thus, when $\text{INF}\ t >> 1$, this equation reduces to:

$$C = \frac{G}{\dot{v}} \qquad (2.8)$$

The infiltration can be therefore expressed as follows (recall that C and G are known quantities):

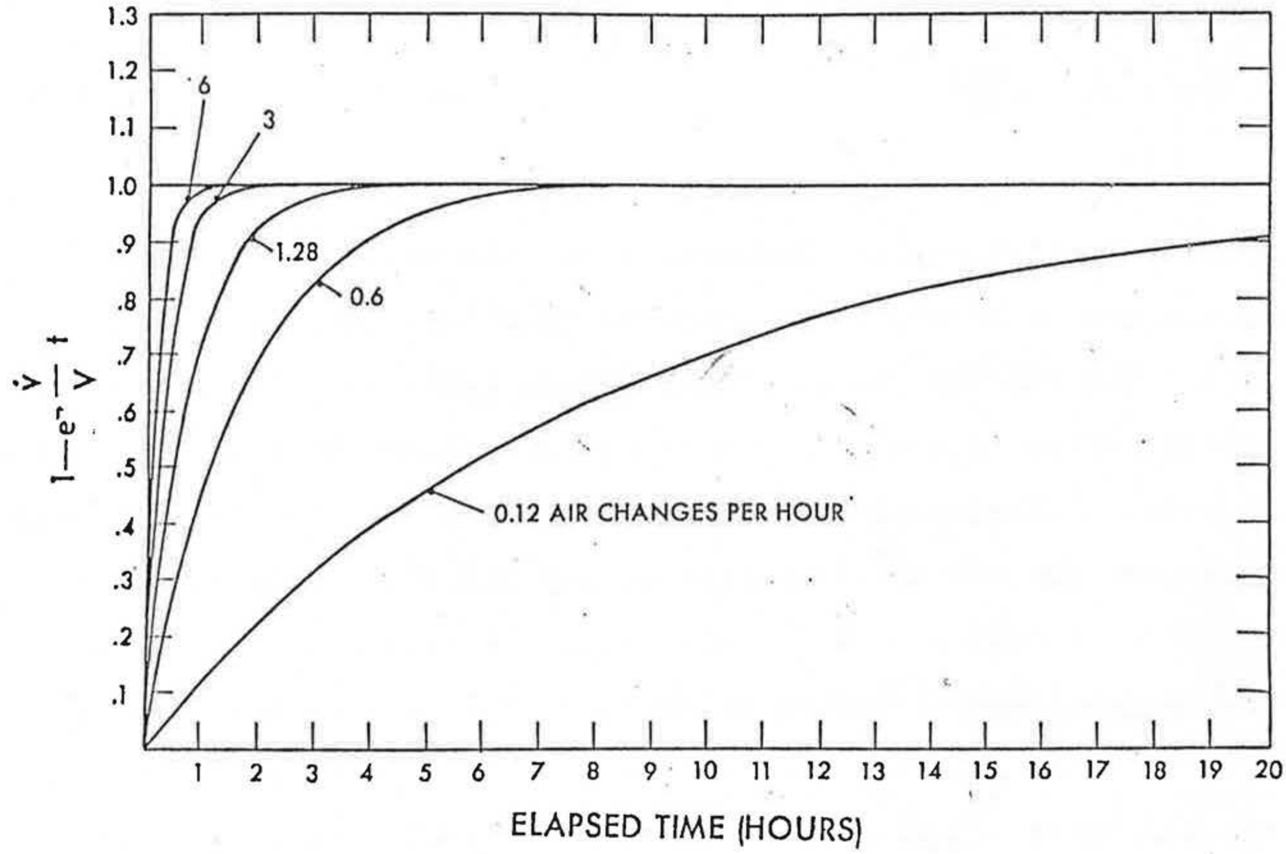
$$\text{INF} = \frac{G}{CV} \qquad (2.9)$$

The primary disadvantage of this approach is that it may take several hours for the equilibrium level to be obtained. For example, if $\text{INF} = 1$ air change per hour then t would have to be 4 hours before the quantity $1-e^{-\text{INF}\ t} \simeq 1$ (within 2%). Furthermore, as the value of infiltration decreases, the time to steady state increases. This relationship is graphed in Figure 2-2. The disadvantage of this approach is the necessity to measure absolute concentration, which can lead to greater measurement error.

Minor variations in these approaches have been tried by several researchers. The first approach is to maintain a constant tracer gas level and carefully measure the rate at which the tracer gas is being injected into the structure. The second, known as the control approach, allows minor variations in the concentration but monitors the rate of injection so that a predetermined concentration of tracer gas is maintained. This method allows for the

Figure 2-2

Time Required to Reach Steady-State
Using the Constant Feed Approach



Source: Hunt (1979).

easy calculation of infiltration. The differential equation that represents this situation is equation 2.5 and can be expressed as follows:

$$V \frac{dc}{dt} = - \dot{v}\ C + G \tag{2.10}$$

Solving for the quantity $\dot{v}$ we obtain:

$$\dot{v} = G/C - V \frac{dc}{dt} \tag{2.11}$$

As Condon, et al. (1978) points out, this form of equation "emphasizes a most attractive feature of the controlled flow technique." Recall that $\dot{v}$ (m^3/sec) represents the total quantity of air entering or leaving the structure. Thus, if the rate change of the tracer concentration is small then $\dot{v}$ can be calculated by dividing G by C. However, a disadvantage to this approach is that the concentration of tracer gas may not stabilize during the first hour of injection.

Once the value of $\dot{v}$ is calculated, it can be used to determine the actual internal volume of the structure and ultimately the infiltration. If the calculated volume is significantly less than the geometric volume of the house, this implies that the tracer gas was not adequately mixed. On the other hand, if the calculated volume is significantly greater than the geometric volume, this indicates that there might be leaks in the distribution system. It is reasonable to expect that the calculated volume is slightly less than the geometric volume as a result of furniture, closets, etc.

It should be noted that although the functional relationships between the constant feed and the control flow approach are identical, the control flow method seeks to maintain a specific concentration while the constant feed approach allows the tracer gas concentration to float.

Finally, one of the most attractive features of the controlled-flow approach is its application for determining the internal air flow patterns--i.e., the multi-chamber problem.

Through the years numerous tracer gases have been used by various researchers to study infiltration. Hunt (n.d.) drawing on the experience of these researchers, developed the following list which summarizes the general characteristics of the ideal tracer gas:

- The gas can be measured easily and accurately at low concentrations.
- The gas must be inexpensive and readily available.
- The gas must not be absorbed by building materials or furnishings.
- The gas must be chemically stable and must not decompose or react with the building materials or the constituents of the air.
- The gas must be nontoxic, non-allergenic, and odorless.
- The gas should be neither flammable nor explosive.
- The density of the gas should be comparable to the density of air.
- The gas should not be present as a background constituent in the air, and there should be no independent generating source in the building being studied.
- The analytic method used to measure the gas should be inexpensive, readily available, easily automated, and have negligible cross-sensitivity with the other constituents of air.

To date no gas and associated monitoring equipment have been identified which comply with all of these characteristics. However, several tracer gases do exist which are safe, easy to use, and relatively inexpensive. The advantages/disadvantages, detection method, monitoring equipment, and cost for several tracer gases are presented in Table 2-1. This list was compiled through the review of numerous reports and conversation with several researchers.

Currently most researchers appear to be using sulfur hexafluoride (SF_6) or nitrous oxide (N_2O) as a result of work performed by Princeton, NBS, and LBL. Each of these research organizations has developed an automatic injection and monitoring system. The design and operation of the Princeton and NBS systems are discussed in great detail by Harrje (1975), while the LBL system is discussed by Condon (1978). The use of microprocessors has greatly expanded system control and data acquisition capabilities. For instance, the Princeton system is capable of collecting data for approximately one week without interruption.

Several researchers have expressed concern about the accuracy of one tracer gas compared to another when measuring air infiltration. These concerns fall into three categories: molecular diffusion, absorption, and settling or stratification. Researchers at LBL (Grimsrud 1980) compared the use of sulfur hexafluoride (SF_6) with nitrous oxide (N_2O) and ethane (CH_4). They determined that use of SF_6 would yield a higher air change rate when compared to N_2O and CH_4 (i.e., air change using SF_6/air changes using N_2O = 1.16 ± .09 and SF_6/CH_4 = 1.09 ± .09). Grimsrud et al. investigated the possibility of molecular diffusion causing the apparent difference in infiltration rates. They hypothesized that if molecular diffusion were the principle infiltration mechanism then lighter gas with higher thermal speeds would exhibit higher infiltration rates when compared to a heavier gas. However, this was found not to be the case; therefore, they discounted this hypothesis. Next the LBL researchers considered the possibility that NO_2 is absorbed more rapidl

TABLE 2-1

TRACER GASES USED IN INFILTRATION STUDIES

TRACER GAS	DETECTION METHOD	COST OF MONITOR	ADVANTAGES	DISADVANTAGES
Sulfer Hexafluoride (SF_6)	Gas Chromatographic Separation Electron Capture Detector I R F	GC: \$4,000 ECD: \$1,600	Inert, non-toxic, non-flammable, detectable in ppb concentrations, low gas volumes required.	Detection equipment response varies with time and therefore requires frequent calibration. Small leaks may lead to measurement error at the ppb level. The gas chromatographic output is in the form of chromatographic peaks--this may cause data acquisition and automation problems. The detector will also respond to other halogented compounds (e.g. refrigerants, aerosol spray can propellants.)
Carbon Monoxide (CO)	Nondispersive infrared Analyzer	Monitor: \$4,000 Auto zero/span \$2,000	Similar molecular weight as air.	Toxic, flammable, low background concentrations
Carbon Dioxide (CO_2)	Nondispersive infrared Analyzer	Monitor: \$4,000 Auto zero/span \$2,000	Non-toxic at levels used in tests, detectable in low ppm concentrations	High background concentration (400-600 ppm) spurious sources (e.g. occupants).
Methane and Ethane (CH_4) (C_2H_6)	Total hydrocarbon analyzer Flame Ionization Detectors with or without gas chromatograph	FID: \$3,150 Auto zero/span \$2,000	Easily detectable, inexpensive monitoring instrumentation (detectable in concentrations ranging from 20 ppm to 400 ppm).	Background concentrations flammable/explosive
Oxygen (O_2)	Paramogentic Analyzer Paramagnetic	∿ \$2,500	Non-toxic	Large background level, difficult to measure small changes accurately
Nitrous Oxide (N_2O)	Infrared Absorption Spectroscope	\$5,000	Detectable in 100 ppm concentrations	Anesthetic; there may be related health hazard
Radon (Rn)	α-particle detector (scintillation counter)	\$1,500-2,000	No extraneous source of tracer gas is required	Monitoring methodology is only in developmental stage; problems remain to be worked out, daughter products increase measurement problems
Kryton and Argon (^{85}Kr and ^{41}Ar)	Geiger counter w/ratemeter	\$1,500-2,000	Radon daughter producers always present ?	Care must be taken during injection so that safe level of radiation exposure is not exceded.
Hydrogen and Helium (H_2 and He)	Thermal Conductivity Detector Katharometer (H_2)	\$2,000	He is non-toxic and stable. Both are detectable at concentration around 0.5% in air.	Light gases may be absorbed into walls; measurement techniques; measure relative concentration, no absolute.
Chlorothene, water ammonia acetone chlorform	Various methods (e.g. acetone concentration can be determined by measuring the change in pH which occures when air containing acetone is absorbed into solution of hydroxylamine hydrochloride).	Varies with method	Readily available	In general this set does not exhibit necessary characteristics for a tracer gas.

than SF_6. However, this hypothesis was not supported by the research results either. Finally, they considered the possibility of settling or stratification of the heavier gases. However, this hypothesis was also discounted since the weight change between air and air plus a few ppb's of SF_6 is insignificant. Therefore, it is not likely that SF_6 will tend to stratify to any significant degree. They conclude that the infiltration rates for each tracer gas is not significantly greater than the measurement error for these monitoring techniques (5-10%). Other researchers have made similar comparisons between various tracer gases; the results are presented in Table 2-2.

The results presented in Table 2-2 indicate that the difference between the two gases compared in each instance is not significant. These results tend to substantiate the LBL conclusion that differences may be a result of monitoring equipment sensitivity.

2.2 Measurement Techniques for Determining Leakage

Several methods are currently available for measuring the leakage of a residential structure. The most popular approach is to use a large fan to pressurize or depressurize the building and then measure the volumetric flow of air caused by the fan. This approach can be applied to the entire house or on specific components. Another approach, known as the infrasonic or AC pressurization method, is to alternately pressurize and depressurize the structure. Thermography has also been used to locate the areas of a structure where leakage occurs. Another approach for locating air leaks uses the properties related to the attenuation of sound waves as they pass through solid materials

Table 2-2

Published Comparisons of Infiltration Rates Determined by Various Tracer Gases[1]

Reference	Tracer Gases	Number of Tests	Results
Warner (7)	$[CO_2]/[\text{Coal Gas}]$	3	1.05 ± 0.18
Collins and Smith (1)	$[^{41}A]/[H_2]$	2	0.93 ± 0.01
Howland et al. (4)	$[^{85}Kr]/[CO_2]$	3	1.00 ± 0.09
Lidwell (6)	$[C_3H_6O]/[N_2O]$	1	0.97
Howard (3)	$[N_2O]/[H_2]$	many	agreement*
Howard (3)	$[N_2O]/[O_2]$	many	agreement*
Hunt and Burch (5)	$[SF_6]/[He]$	6	1.17 ± 0.14
Grimsrud et al. (2)	$[SF_6]/[N_2O]$	7	1.16 ± 0.09
Grimsrud et al. (2)	$[SF_6]/[CH_4]$	4	1.09 ± 0.09
Grimsrud et al. (2)	$[SF_6]/[C_2H_6]$	1	0.97

[1] The results quoted are the mean values of the ratios of the measured air change rates. Furthermore, the ratio is formed by dividing the air change rate of the heavier gas by the air change rate of the lighter gas.

*The results of this research were not quantified. However, the author states that the results of the tracer gas tests showed close agreement between the indicated tracer gases.

Adapted from: Grimsrud, D. T. et al., (1980).

Table 2-2 (continued)

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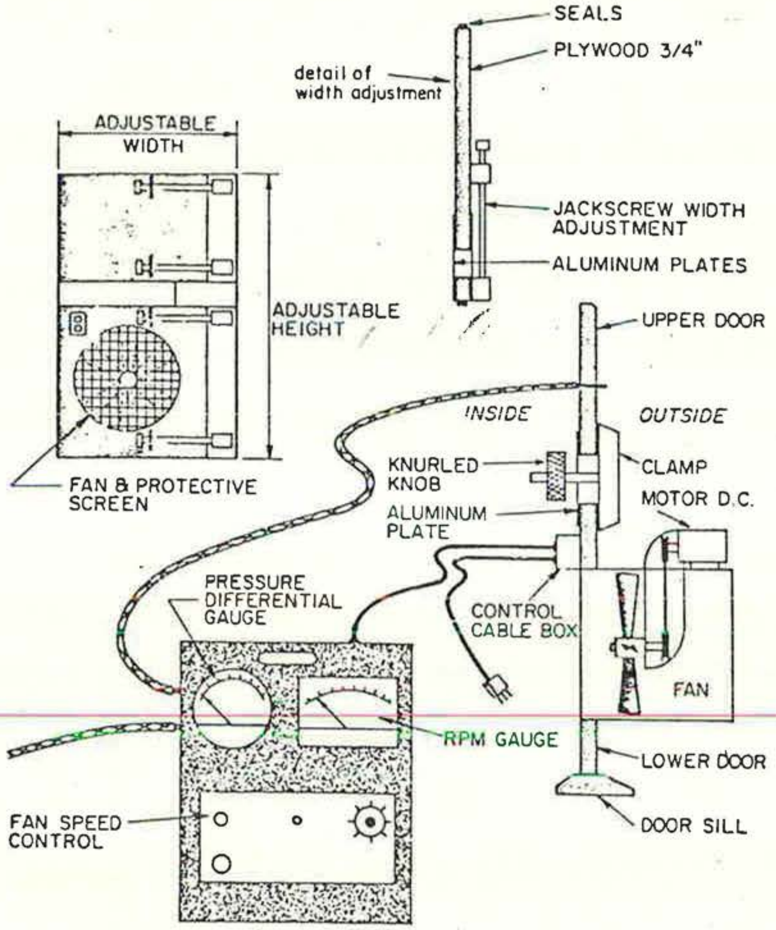
with cracks and holes. The last two approaches mentioned are, in general, qualitative tools, while the pressurization techniques are quantitative in nature. These and other leakage measurements and methodologies will be discussed in this section.

2.2.1 Fan Pressurization Technique

Early air infiltration researchers realized that it was possible to use large fans to pressurize or depressurize a house and thus characterize the rate of air leakage as a function of the pressure difference across the fan. The construction details of a blower door are presented in Figure 2-3. A vaneaxial fan, driven by a variable speed motor is attached to a large piece of plywood and can be adjusted to fit in a typical exterior doorway. In the laboratory the relationship between the volumetric flow of air and the pressure difference across the fan is determined as a function of the speed of the motor. The final piece of equipment required for this system is a differential pressure transducer. To determine the leakage function of the house, the operator simply varies the speed of the fan to produce a series of pressure differences. Since the pressure differential is significantly greater than that which is produced by the wind or inside-outside temperature difference, this technique measures only the response of the building. However, this approach causes a uniform pressure throughout the house which does not naturally occur under normal weather conditions. Furthermore, the imposed pressure may push windows and doors away from their seals causing high leakage rates.

This approach can be used to locate leaks or to determine the percent of air leakage which occurs through various building components. To locate leaks, smoke sticks are passed around

Figure 2-3
Blower Door and Control Panel



Source: Blomsterberg, (1979a).

areas suspected of leaking. If the leaks are not too large they can be fixed immediately with caulking or weatherstripping, greatly reducing the amount of leakage. Leakage caused by specific building components such as doors, windows, vents, electrical outlets, or entire walls can be determined by initially pressurizing the building and then selectively sealing the various components. The decrease in pressure resulting from each sealed component is proportional to a decrease in air flow. The results of such studies will be presented in Chapter 3 of this report.

The relationship between the rate of air leakage and pressure difference has been modeled by the following equation:

$$\dot{V} = K \Delta P^{n}$$

$\dot{V}$ = the volumetric flow rate of air

K = flow coefficient equal to the flow rate at $\Delta P = 1 \text{Pa}$.

ΔP = the pressure difference across the door

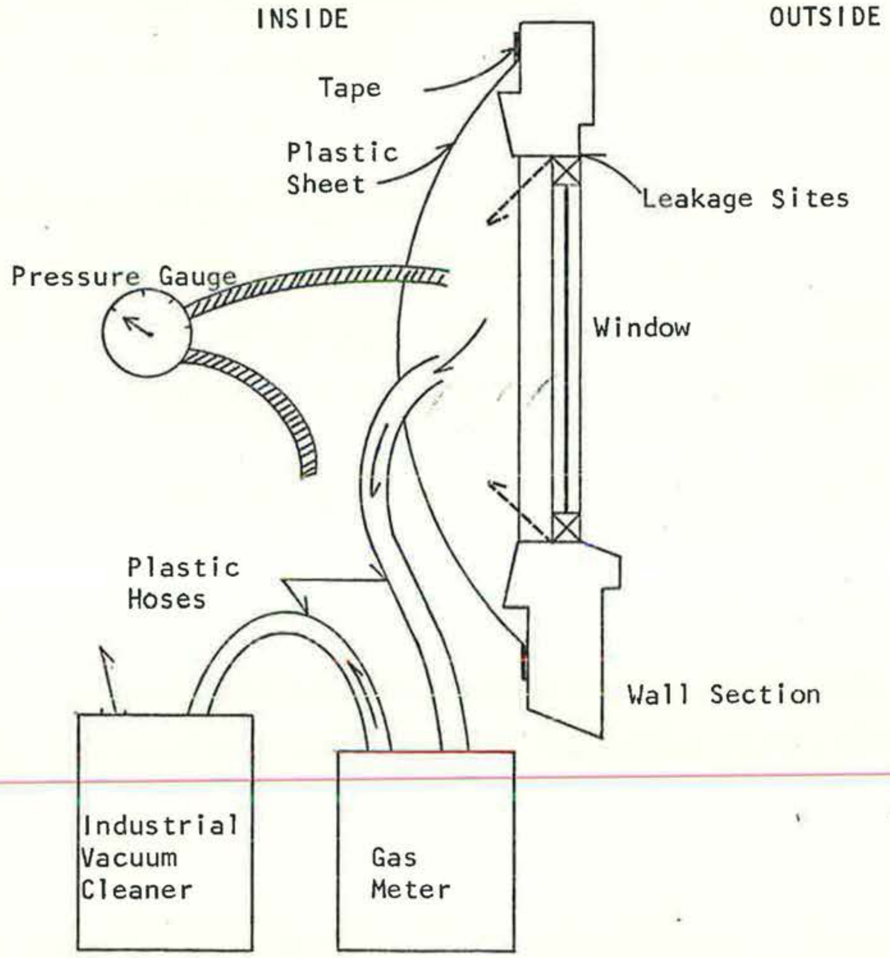
n = the flow exponent which has values usually between 1/2 for turbulent flow to 1 for laminar flow

This modeling approach presumes that the cracks and holes are uniformly distributed around the house. Using this formulation it is not surprising to find out that the values of K and n vary greatly between houses since the number, location, and size of the actual openings causing the leakage vary greatly from house to house. Thus, when using the pressurization technique it is necessary to specify the values for K and n as well as ΔP.

A similar but smaller apparatus can be used to measure the leakage of specific windows and doors. A schematic of the equipment necessary for this approach is presented in Figure 2-4.

Figure 2-4

Test Arrangement for Window Leakage Measurements



Adapted from: Blomsterberg (1979a)

The object here is to seal a plastic sheet around a window, for instance, and then use a vacuum pump to draw air through the leaks around the window. The pressure drop across the plastic sheet is then proportional to the rate at which the air is flowing through the cracks. It is possible to use this set-up to evaluate the effectiveness of caulking or weatherstripping (see Chapter 5).

The researchers at LBL recognized that the use of fan pressurization imposes such high pressure differentials that it masks over the physical phenomena which are the driving forces behind infiltration. Thus, they developed a measurement technique by which the leakage could be determined even at low pressures.

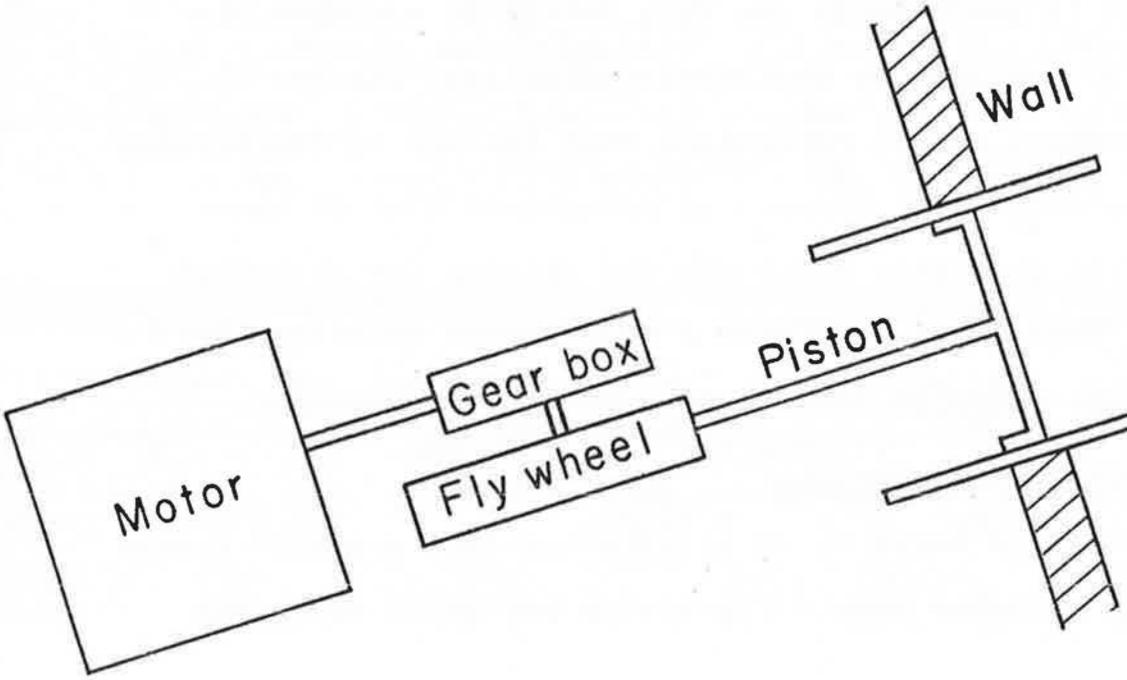
2.2.2 Infrasonic Technique

This approach is based on an alternating (AC) pressure source installed in an exterior door. The system was built such that the frequency of operation and displacement volume could be varied over a wide range of values. A schematic of this system is presented in Figure 2-5. The following description of the equipment has been excerpted from Sherman et al. (1979):

> "the source of the pressure signal is a large cross section (~ 1 m^2) rectangular piston which moves in and out of the shell through a suitably sized guide. The guide is installed in an exterior door of the test structure. As the piston moves outward through the guide the volume of the house is increased; as it moves inward the volume decreases. The guide is made of plywood and has teflon seals all around it to minimize both friction and air leakage through the guide."
>
> "The piston is connected via a connecting rod to a light flywheel. The diameter of the flywheel is about 0.5 m; there are nine different holes in the flywheel to allow different displacements of the piston during the drive stroke. The maximum displacement peak to peak is about 0.3 m^3.
>
> "The flywheel is driven through a gearbox by a variable speed 3/4 hp motor. With the current arrangement of motor, gearbox, piston and guide the frequency of oscillation ranges between 2 to 250 rpm [cycles per minute]."

Figure 2-5

Schematic of AC Pressurization Equipment



Source: Sherman, (1979).

As with the blower door, it is possible to produce a curve which represents the relationship between leakage and pressure difference. The field studies using this approach indicated that as $\Delta P \rightarrow 0$ the amount of leakage remains finite. Sherman et al. conclude that this may indeed be a physical phenomenon which is characteristic of a structure even when the infiltration driving forces of wind and temperature difference both approach zero.

2.2.3 Thermography

Another approach for measuring, at least qualitatively, the air leakage of a building is thermography. Thermography is the process of converting the heat emitted from an object into a visible picture. Some infrared scanning systems use TV-like equipment which produces a dynamic picture while other thermographic cameras produce a simple snapshot of the heat flow patterns.

With a typical thermographic scanning system the radiation is focuses from the object onto an infrared sensitive indium-antimonide detector, the voltage variations of which are amplified and shown on a CRT display. The difference in heat radiation appears as tones of gray or color variations in the picture.

A thermographic scan can be made of a building from the inside or outside. For locating air leaks the best results are obtained when the inside temperature is significantly different from the outside temperature. In addition to locating leaks this approach can be used to determine if a particular retrofit has effectively sealed the leak.

2.2.4 Acoustic Techniques

Researchers at Bolt, Beranek, and Newman, Inc. have developed a system which can be used to locate air leaks by using a simple sound source and sound monitor. This approach is based on the fact that sound waves pass readily through the cracks and openings which are responsible for air infiltration.

The acoustic leak location method as described by Keast (1979) is based on the fact that

> sound is the result of small pressure fluctuation about the ambient pressure of the atmosphere. These pressure fluctuations propagate as longitudinal waves through the air. When sound waves strike a solid object such as a building wall, they cause it to vibrate. This vibration in turn produces a new sound on the other side of the wall. The sound produced on the 'output' side of the wall is, in general, greatly reduced in amplitude compared to the sound that caused the wall to vibrate in the first place. The output sound will be altered in frequency content as well. The ratio of the input sound energy to the output sound energy of a wall, under carefully controlled conditions, is called the "transmission coefficient" of the wall. Ten times the logarithm of this ratio is the "transmission loss" of the wall, in decibels (dB). The transmission loss of typical residential structures varies from about 20 dB at 100 Hz to 40 dB at 2000 Hz or more. In general, the more massive a structure, the greater its transmission loss will be.

The use of this technique consists of placing a sound source inside the house and then listening to the sound on the other side. The sound source should be steady and high pitched to yield the greatest attenuation of sound. The listening equipment consists of a battery powered microphone connected to a battery-powered set of headphones. Leaks are located by searching for areas where the sound increases in volume. Areas where leakage is suspected should be compared to similar areas where no leakage exists. Although this approach is simple, effective, and an inexpensive means for locating air leaks, it cannot quantify the rate of air leakage. If the actual volumetric flow of air is required then one of the pressurization techniques should be used.

2.2.5 Pressure Attenuation Technique

A final leakage measurement methodology involves the sudden release of compressed air into the house. The quick release of the air will cause instantaneous pressurization of the structure. As the air leaks out, the pressure will return to the normal indoor level. The rate at which this is accomplished is proportional to the leakiness of the structure.

2.2.6 Summary of Leakage Measurement Techniques

The advantages/disadvantages and estimated cost of the equipment required for the various leakage measurement methodologies are presented in Table 2-3. Due to the ease of operation and relatively low cost, most researchers use the blower door to determine leakage. However, the interesting results obtained from the LBL infrasonic approach may encourage the use of this and other non-steady-state measurement techniques.

2.3 Additional Measurement Equipment and Physical Information Necessary for the Determination of Air Infiltration or Leakage

In addition to the leakage and infiltration measurement techniques already discussed a large number of other physical quantities must be measured. For instance, the indoor-outdoor temperatures, wind speed and direction, and the humidity levels are all necessary to determine the impact of physical factors on infiltration. Fortunately, the use of microprocessors now makes it possible to monitor literally hundreds of quantities and allows the researcher to completely automate the data collection and storage process.

TABLE 2-2

LEAKAGE MEASUREMENTS METHODOLOGIES

METHOD	EST. EQUIPMENT COST	ADVANTAGES	DISADVANTAGES
Fan Pressurization (blower door)	$ 300	Quantitative; provides rate of air leakage as a function of pressure differential.	Requires removal of door or window takes some time to set up, unreliable at low ΔP, does not simulate true environmental conditions, noise may be a problem.
Portable test kits for individual doors or windows	$1,500	Gives leakage of specific windows, doors, walls, etc.; it is quantitave (i.e. provides leakage as a function of pressure difference)	Expensive, does not give leakage function of entire residence
Infrasonic Technique (A C Piston)	$ 400	Quantitative; provides leakage as a function of pressure difference and can be operated at low pressure differences. Since the frequency of the system is set, the effects of wind and temperature do not interfere.	Difficult to fabricate and set up, relatively new technique
Infrared Thermography	$10,000 or rental	Locates heat loss areas easily	Not quantitative
Acoustic Leak Detection	$ 200	Easy, straight forward techniques, inexpensive	Not quantitative; only identifies leaks, (not their magnitude)
Pressure Attenuation Technique	$ 100 (excluding pressure transducers)	Non steady-state, may reduce interference from wind and temperature effects.	Requires substantial amounts of compressed air and sensitive pressure detectors
Smoke Sticks and Pencils	$ 20	Cheap, easy to use, readily identifies major leaks	Not quantitative.

Table 2-4 lists several of the quantities monitored at the Princeton Twin Rivers Project by their microprocessor. The quantities indicated in the table are those which are directly relevant to infiltration; a large number of other quantities were monitored by the Princeton researchers but do not relate to infiltration directly.

Temperature and pressure are probably the most important quantities to measure accurately. Indoor and outdoor temperatures can be easily measured with relatively inexpensive thermistors. These thermistors can be located in several parts of the house and connected to the central microprocessor. Atmospheric and surface pressures can be measured using electronic transducers. The principal disadvantage of this approach is the expense: the cost of a pressure transducer ranges from \$150 to \$1000. Researchers at LBL have minimized the number of pressure transducers required per house by installing a network of plastic tubes throughout the house. These tubes are connected to a single pressure transducer via a manifold arrangement and are used to measure the surface pressures on the exterior walls.

The amount of time that doors and windows are open is another factor which has a major impact on the rate of air exchange. The use of burglar switches to energize the motor that drives a potentiometer is one means to determine the length of time a window or door is open but it does not indicate the degree to which the window was opened. Furthermore, open windows can cause severe problems when using a tracer gas since they can serve as

Table 2-4

General Instrumentation
for Infiltration Research

Quantity to be Measured	Instrumentation	Comments
Temperature	Linear compensated thermistor	direct voltage output small, accurate, inexpensive and reasonable response time
Barometric or Surface Pressure	strain gauge or capacitance type pressure transducer	accurate but expensive voltage output proportional to pressure
Wind Speed (average)	cup anemmeter connected to digital counter	digital signal must be directed through a digital to analog converter
Wind Speed (instantaneous)	cup anemmeter connected to a direct current generator	current generated is proportional to wind speed
Wind Direction	cup anemmeter connected to a potentiometer	displacement proportional to linear voltage output
Humidity	dual-bobbin moisture sensor, psychrometers or hygrometer	
Window/Door Openings	burglar switches used to energize a synchronous motor connected to a potentiometer	the potentiometer rotates at a constant rate so that the voltage output is proportional to open time

a short circuit; thus the assumption of perfect mixing is no longer applicable.

In addition to these quantities there are a number of items which should be noted about the house being tested. For instance, the orientation of the house with respect to the prevailing winds will most likely have a major impact on infiltration; the type of house (ranch, two-story, etc.) could be significant; and the general landscape of the immediate surroundings will impact the infiltration as well. Table 2-5 lists the quantities which should be measured and the items which should be recorded via site inspection.

2.4 Summary of Measurement Techniques

Currently the use of tracer gases and fan pressurization techniques are the principal means to determine infiltration and leakage. However, recent work with non-steady-state techniques has allowed researchers to approach zero ΔP without interference from wind or temperature difference. This low pressure regime is very relevant to the study of infiltration since it is these low pressures which the structure is responding to in reality. Such techniques as thermography and sound attenuation are helpful in locating leaks. Furthermore, they can be used to evaluate the effectiveness of retrofit work as well. However, for the air infiltration researcher who is searching for a relationship between the physical situation and the resulting infiltration, nonquantifiable methods are of little value.

Table 2-5

Quantities to be Measured or Observed at the Test Site

Observations to be Made

- Outside
  - Type of house/Construction materials
  - Orientation
  - Crackage around frame, windows, doors, vents, etc.
  - Dimensions
  - Windows and Doors
    - type/number/dimensions
    - orientation
    - materials
    - glazing
    - condition of caulking
    - condition of weatherstripping
    - storms/shutters/drapes, etc.
  - Insulation--type and amount
  - Condition of vapor barrier
  - Number/Type of vents
  - General landscaping

Items to Be Measured

- Outside
  - Temperature
  - Wind speed and direction
  - Humidity
  - Barometric Pressure

- Inside
  - Temperature in several locations
  - Window/Door open-time
  - Vent open-time
  - Heating system energy consumption
  - Air conditioner energy consumption
  - On-off times of heating/air condition systems
  - Fluid flow rate of energy delivery system
  - Temperature of fluid
  - Humidity

3.0 RESIDENTIAL AIR INFILTRATION CASE STUDIES

The vast majority of residential air infiltration research evaluates the effect that each of the following have on the level of infiltration: weather conditions, occupant behavior, and the quality and type of construction. Some of the case studies reviewed in the preparation of this report were based on data obtained from a single house; however, the majority of the case studies involved a larger number of residential structures. For instance, a recent study in Canada by Beach (1979) determined the amount of air leakage for 67 newly constructed houses built by 9 different contractors.

The review of the research revealed that the case studies performed usually fall into one of the following three categories:

- determination of infiltration using tracer gases
- determination of air leakage using fan pressurization techniques
- comparison of infiltration rates obtained from the tracer gas technique with leakage rates obtained from fan pressurization measurements.

Case studies using tracer gases dominate the air infiltration research. However, in recent years, fan pressurization techniques have been used successfully to determine which building components or regions of the house are responsible for the air leaks. Furthermore, since fan pressurization is, in general, easier, more reliable, and less costly to perform, several researchers have studied the relationship between leakage and infiltration. If a reliable predictive model can be developed that relates leakages to infiltration then the cost to measure infiltration would be substantially reduced. The case studies relevant to each of the categories outlined above will be presented in this chapter.

3.1 Case Studies Involving the Measurement of Infiltration Directly

As pointed out in Chapter 2 the most popular method for measuring infiltration directly is with the use of tracer gases. A recent example of such research effort was conducted by Reeves et al. (1979) which studied air infiltration in 9 residential structures (6 detached houses and 3 townhouse apartments). The report by Reeves is a summary of the research performed by Sepsy et al. (1977). The object of their study was to formulate an equation which could be used to predict the level of infiltration as a function of physical parameters. Infiltration was measured using the tracer gas decay method. Sulfur hexafluoride (SF_6) was automatically injected every three hours, and the SF_6 concentration measured every 15 minutes.

The researchers initially tried to fit their data (1879 hours worth of actual observation) to a regression equation of the form:

$$INF = A + B\,\Delta T + CW$$

but as a result of the large variation in the regression coefficients they turned to a completely new formulation. The researchers then tried an approach based on physical variables and associated theory pertinent to air infiltration. The physical parameters of interest were crack length and width, the inside-outside pressure difference developed as a result of the prevailing wind and temperature conditions, and the location of the neutral zone. At the outset Reeves felt that "the physical models would, at best, be completely deterministic from theory alone or require, at most, a single statistical regression coefficient which would be somewhat constant for all residences..."

Two relationships which relate pressure differences respectively to temperature and to wind were obtained form ASHRAE (1977). The first equation describes the pressure difference resulting from the inside-outside temperature difference. The temperature difference causes a difference in the density of air which in turn causes the inside-outside pressure difference. The pressure difference can be expressed as follows:

$$\Delta P_T = 34\ Ph\ (1/T_o - 1/T_i)$$

where

ΔP_T = The theoretical pressure difference across the enclosure due to the so-called stack effect (Pa)

P = Absolute atmospheric pressure (kPa)

h = Effective stack height; Reeves, et al. used the following values in their research: Two story, h=2.4m; Split level, h=1.8m; and ranch, h=1.2m.

$T_{o,i}$ = Absolute outside and inside temperatures (^{o}k)

The second equation describes the pressure difference produced across the structure by wind. The relationship is as follows:

$$\Delta P_W = 176.5\ (1/T_o)\ W^2$$

where

ΔP_W = The theoretical pressure difference across the envelope due to the wind (Pa)

W = Wind speed (m/s)

In addition to the above theoretical ΔP's, Reeves, et al. adopted a method to determine the equivalent crack length of a structure as presented in ASHRAE (1977). The crack length for each structure was multiplied by the appropriate air infiltration factor. The sum of these values was then divided by the factor for non-weatherstripped, average fit, double hung, wood windows to obtain the equivalent crack length for that structure.

They then derived a set of physical models incorporating pressure differences, wind direction, and equivalent crack length per exposure that took the following form:

$$INF = \beta_o f\ (C_i, \Delta P_i)$$

where

β_o = Statistical regression coefficient

C_i = Equivalent crack lengths for the $_i$th exposure

ΔP_i = Theoretical pressure difference due to temperature and wind effects on the $_i$th exposure

The velocity term used in the equation for ΔP_W was non-zero only when the wind direction was normal to that exposure; this approach, therefore, accounted for wind direction. However, due to the failure of this formulation to yield consistent values for β_o other functional relationships were developed.

The relationship which Reeves, et al. believe to be the best representation of the data has the form:

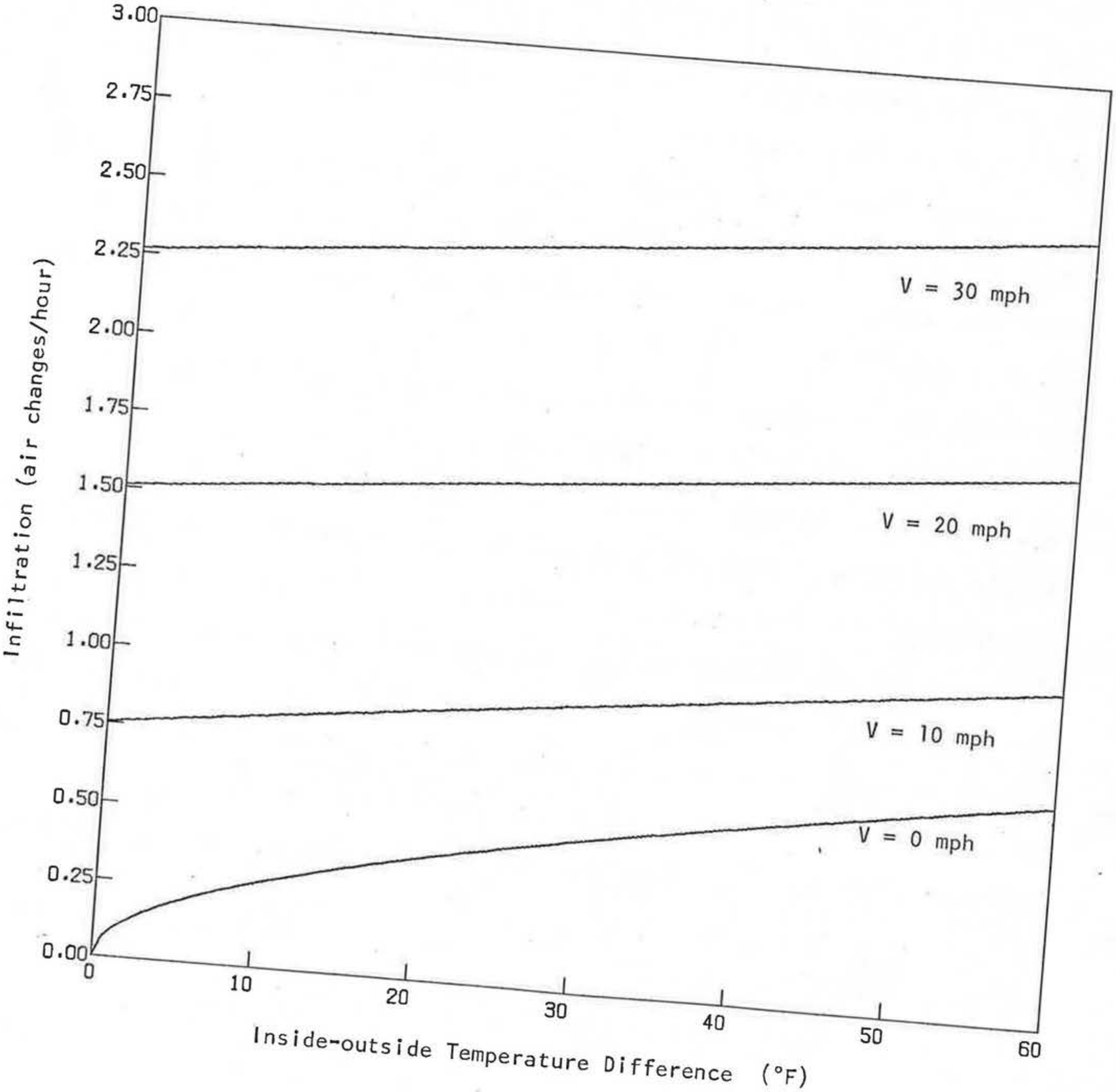
$$INF = \beta_o\ C_T\ (\ 4\ \Delta P_T\ \ + \sqrt{2}\,\Delta P_W)^{\frac{1}{2}}$$

The regression coefficient β_o can be considered as a measure of the quality of construction (workmanship) and possible other unaccounted factors. C_T is the <u>total</u> equivalent crack length for the entire structure. The value of this function for various wind and temperature conditions ($C_T = 29.7m^2$, $T_i = 292^0K$, and $h = 2.4m$) is presented in Figure 3-1.

The energy research conducted in Twin Rivers, New Jersey has produced a very comprehensive view of the energy use in residential structures. The Twin Rivers project is the most ambitious research effort yet undertaken in the area of residential energy consumption.

Figure 3-1

Infiltration as a Function of Inside-Outside Temperature Difference and Wind Speed



$INF = \beta_o \; C_T(4\Delta P_T + \sqrt{2}\,\Delta P_W)^{\frac{1}{2}}$

Air infiltration was only one of the many quantities measured in the course of that research; the fact that gas consumption, electricity consumed by the electrical appliances, and occupant energy-related behavior were also monitored is indicative of the scale and depth of the research.

Socolow (1977) summarizes a collection of eleven articles that tell the story of a five-year research effort to learn about the numerous energy functions of townhouses and their occupants in Twin Rivers, New Jersey. The researchers from Princeton University describe their studies and results which range from furnace retrofits to occupant feedback experiments.

The infiltration-related research has been summarized by Harrje et al. (1977). In that report Harrje presents the results obtained in the 5 years of research of 29 townhouses. Sulfur hexafluoride (SF_6) was used to measure the level of infiltration via the tracer gas decay method. An automated system was developed by the Princeton researchers which can inject the tracer gas, take air samples, and store the results on cassette tapes. The system is capable of operating for approximately one week without attention. This allows the occupants to go about their daily routines with a minimum of inconvenience.

The analysis of the data indicated that the following six independent variables were related to the level of infiltration:

ΔT - Inside-outside temperature difference

W - Wind speed

Θ - Wind direction

G - Rate of gas consumption for space and water heating, ovens, stoves, etc.

F and B- The fraction of time the front and basement doors were open

A regression equation on these variables was developed for two situations: low and high speeds. The results are as follows:

Low Wind Speeds:

$$INF = A_1 + B_1\ \Delta T + C_1\ W \cos(\Theta - \Theta_o) + D_1 + E_1\ B + F_1\ F$$
$$= 0.19 + 0.005\ \Delta T + 0.012\ W \cos(\Theta - \Theta_o) + 0.003\ G + 0.0002\ B + 0.009\ F$$

High Wind Speeds:

$$INF = A_2 + B_2\ \Delta T\ W \cos(\Theta - \Theta_o) + D_2\ G$$
$$= 0.31 + 0.001\ \Delta T\ W \cos(\Theta - \Theta_o) + 0.023\ G$$

In addition to determining the above relationships, the researchers installed and evaluated the following four retrofit packages:

- "Group A" retrofits concentrated on the attic area, increasing insulation levels and sealing cracks between the attic frame floor and the masonry firewalls.
- "Group B" retrofits concentrated on the living space; the objective was to improve door and window seals by caulking and weatherstripping.
- "Group C" retrofits concentrated on the cellar; the objective was to reduce energy loss through leaky air ducts and registers and to decrease the losses associated with the hot water storage tank.
- "Group D" retrofits closed the air shaft surrounding the furnace flue townhouses which connected the basement to the attic.

Each of these retrofit groups decreases the level of infiltration in the townhouses thus making them more energy efficient.

Retrofit Groups A and D were estimated to cost a total of \$190 (time and labor) while Group B costs \$75 and Group C \$135. It was estimated that given the energy savings resulting from these retrofits, the cost could be recouped in approximately seven years.

Luck (1977) determined that humidity levels may also have an impact on the level of infiltration, especially in cold climates where winter humidities are reduced drastically. His data indicate that infiltration levels can be reduced by a factor of 2 or 3 as humidity levels increase. He feels that the swelling of doors, windows, and other building components decreases crack size and causes the measured decrease in infiltration.

Intially, Luck felt that the relationship

$$INF = A + BW^2 + C\ (1/T_o - 1/T_i)$$

was the appropriate equation to quantify air infiltration. However, when their data failed to confirm this relationship they looked for the physical cause for the discrepancy. To account for the change in humidity, Luck adjusted the relationship as follows:

$$INF = INF_o\ \{A + BW^2 + C\ (1/T_o - 1/T_i)\}$$

where INF_o is an adjustment factor for the levels of humidity.

Hunt (1975) performed air infiltration tests on a four bedroom townhouse which was located in an environmental chamber. This approach allowed Hunt to research the effects of inside-outside temperature differences (stack effect) without the interference of wind interaction. An interesting finding from this research was that infiltration did not vanish as inside-outside temperature difference approached zero. Hunt et al. did not substantiate this premise with actual measurements since the minimum ΔT obtained was $\sim 5^\circ$ C. However, they speculate that non-zero infiltration may be possible at $\Delta T = 0$ due to local disturbances. Furthermore, they found that sealing windows and doors near the neutral zone had little effect on infiltration in the absence of wind. This result was also observed by Howard (1966).

The realtionship which represents the best fit to their data was of the form:

$$INF = A + B\ \Delta T$$

where the values of the regression coefficients A and B were calculated to be 0.117 and 0.0108 respectively. The infiltration data for this relationship were obtained using three air sampling techniques. The first was to take bag samples in various rooms according to a specified time schedule. The second approach used a network of 16 tubes located throughout the house which were connected to a single tracer gas measurement device. Thus, samples could be drawn from any point in the house to determine the concentration of the tracer gas at that location. The final method was to sample the return air duct of the heating system. However, the variation in the level of infiltration using these three approaches was very small, amounting to only 0.06 air changes per hour.

Tamura (1964) observed that infiltration rates during the summer were proportional to the square of the wind speed, while during the winter the stack effect and furnace operation also influenced infiltration. One of the most significant findings was that the effects of wind and temperature are subadditive -- i.e., the expected effect due to wind alone plus the effect due to temperature alone is always greater than the measured infiltration level for an actual wind/temperature condition.

Prior to 1964, the most significant research on residential infiltration was conducted by Dick, et al. (1949, 1950, and 1951). Dick 1949 and 1951 are reports on the research performed at two sites in England. Dick (1951) considered the infiltration of 8 sheltered two-story semi-attached houses located in Buchnalls Close. In these studies the tracer gas was helium and the concentrations of the tracer were measured using a katharometer. Dick, et al. were concerned about the effects windows have on infiltration so they maintained a log of window openings throughout their study. During the day, random visits were made to the research site at which time the disposition of the windows were recorded.

The houses at this site were studied in three different operating modes. The first mode was unoccupied with all doors, vents, and windows closed; the second mode was unoccupied but with doors, vents, and windows operated by research personnel to simulate occupancy; finally, the third mode was occupied. The tracer gas injection and sampling systems were designed so that they would not interfere with the living patterns of the occupants. The system consisted of two sets of copper tubes (one for injection and one for sampling) attached to at least three walls in every room. This allowed for injection of the tracer gas into all or some of the rooms and permitted detailed sampling of the tracer gas concentration in one room or the entire house. One advantage of this injection sampling process is that the relative movement of the tracer gas from one room to another can be observed. Dick, et al. were therefore able to distinguish between air movement between rooms and infiltration.

The results of the research on the sheltered houses are summarized by the following relationships:

CLOSED	OPENED	OCCUPIED
$INF_W = 0.16W$	$INF_W = (0.16 + 0.07n)W$	$INF_W = (0.16 + 0.036n)W$
for $W^2/\Delta T > 2$	$W^2/\Delta T > 1$	$W^2/\Delta T > 3$
$INF_{\Delta T} = 0.22\ \Delta T^{\frac{1}{2}}$	$INF_{\Delta T} = (0.22 + 0.05n)\ \Delta T^{\frac{1}{2}}$	$INF_{\Delta T} = (0.22 + 0.07n)\ \Delta T^{\frac{1}{2}}$
for $W^2/\Delta T < 2$	$W^2/\Delta T < 1$	$W^2/\Delta T < 3$

In these equations, n refers to the number of window vents open at a particular point in time. The critical value of the ratio

$W^2/\Delta T$ was found to be the dividing line between two distinct infiltration regimes (i.e., one regime where wind effects dominate, the other where temperature effects dominate). Note that there are no constant terms in the above relationship; that is, each term is multiplied by ΔT or W. Dick believes that this result occurred because these houses had sealed combustion heating systems; the cycling of the heating system therefore did not have a great effect on infiltration.

Dick (1949) presents the research performed at Abbots Landley where 20 exposed two story houses were studied using the tracer gas decay method. The operation of windows and the associated effect on infiltration was studied in the research as well. It was found that 70% of window openings were correlated with external temperature and that an additional 10% were related to wind conditions.

The results of their research can be summarized by the following two relationships:

vent openings only: $INF = A + (B + Cn)\,W + En$

vent and window openings: $INF + A + (B + Cn + Dm)\,W + En + Fm$

where:

$A = 0.870$; $B = 0.075$; $C = 0.027$; $D = 0.038$; $E = 0230$; $F = 0.322$

Note that even if ΔT and W are zero and all the vents and windows are closed, the infiltration at this site would be non-zero unlike the results obtained at Buchnalls Close.

In addition to the research projects presented above, there have been numerous other case studies which used tracer gases to determine the level of infiltration directly.

Table 3-1 is a summary of the major residential air infiltration research using the tracer gas technique over the past 30 years. The next section will cover the research efforts which used the fan pressurization technique to measure the rate of air leakage in houses.

3.2 Case Studies Involving the Measurement of Air Leakage

During the past few years, several research studies have been devoted to assessing the rate of air leakage through various building components or through the entire house. The review of the literature revealed that most researchers chose the fan pressurization technique for this purpose. (A more complete description of this and other leakage measurement techniques is presented in Section 2.2).

One of the major attributes of this approach is the ability to quantify the leakage function of the building without the interference of wind or temperature effects. Thus, this approach is ideal for evaluating the relative tightness of the structure and the effectiveness of the retrofit measures. Furthermore, the Swedish Building Code requires that new houses to be built such that the leakage at 50 Pa is less than or equal to 3.0 air changes per hour. With the emphasis on reducing leakage it is likely that the use of the fan pressurization approach will receive more attention in the future.

Beach (1979) recently completed a most interesting research project during which a total of 67 houses were tested and the rate of leakage measured. Five house types were included in the study. These houses were constructed using standard construction practices by nine contractors during 1978. As part of this study detailed

TABLE 3-1

Tracer Gas Case Studies

RESEARCHER	NUMBER AND TYPES OF HOUSES	MEASUREMENT TECHNIQUE	MODEL OR RELATIONSHIP	SUMMARY
Reeves (1979)	6 houses and 3 apts. • 4 two stories • 1 split level • 1 Ranch • 3 Townhouse All test houses had central forced air furnaces.	Tracer gas decay method using SF_6 as tracer. Automatic injection and sampling.	$INF = \beta_o C_T (4\Delta P_T + \sqrt{2}\,\Delta P_w)\ 1/2$ $\Delta P_T = .34\ Ph\ (1/T_o - 1/T_i)$ $\Delta P_w = 176.5\ (1/T_o)\ V^2$ β_o = a regression coefficient $\beta_o = 1.55 \pm .64$ C_T = total crack length of structured	The 6 houses and 3 apartments were monitored for a total of 1879 hours. This data, stored on computer magnetic tape, is available through the Electric Power Research Institute (EPRI) the sponsor of this research. The researchers first considered regression relationships of the form: $INF = A + B\Delta T + CV$ but were not satisfied with the statisical variation in the regression coefficient. They then investigated other infiltration equations based on physical phenominia such as crack length and width and differential pressure within the structure due to temperature and wind. The constant βo accounts for the quality of workmanship and other factors not address directly.
Harrje (1977)	2 townhouses	Tracer gas decay method using SF_6	House #1: • $INF = A_1 + B_1\,\Delta T + C_1 \cos(\Theta - \Theta_1) + D_1 G + E_1 F + F_1 B$ for low winds: $W < 9.7$ km/hr. • $INF = A_1^* + B_1^*\,\Delta T\ W \cos(\Theta - \Theta_1^*) + C_1^* G$ for high winds: $W > 9.7$ km/hr.	From the available data it appears that for each house there are 6 independent variables; ΔT, V, wind direction, rate of gas consumption, front door opening and basement door openings. As can be seen by the regression expression the relationship is quite complex, however, the functional dependence on wind direction should be noted.
Luck (1977)	1 one story house forced hot air system	Tracer gas decay method using chlorothene	• $INF = INF_o \{ A + BW^2 + C (1/To - 1/Ti) \}$ Where INF_o = base infiltration rate adjusted for level of humidity.	The objective of this research was to substantiate the relationship $INF = A + Bv^2 + C \{ 1/T_o - 1/T_i \}$ however, the data collected showed a poor correlation with this relationship. It was soon discovered that the level of absolute humidity was changing with time and therefore altering the infiltration level. The reseachers feel that the change in moisture level in the building products is large enough to affect infiltration especially in cold climates. The data indicates that a 2 to 3 fold reduction can occur as humidity levels increased. Thus the swelling of the doors, windows, and other building components causes a decrease in crack size.

TABLE 3 - 1 (con't)

Tracer Gas Case Studies

RESEARCHER	NUMBER AND TYPES OF HOUSES	MEASUREMENT TECHNIQUE	MODEL OR RELATIONSHIP	SUMMARY
Hunt (1975)	1-four bedroom townhouse located in environmental chamber. The townhouse has a central hot air heating system.	Tracer gas decay method using SF_6 and helium (He)	• $INF = A + B\ \Delta T$	The effects inside-outside temperature has on the structure was analyzed since no wind effects were present in the environmental chamber to interfer. They tried three types of sampling techniques; first, bag samples; second, network of 16 plastic tubes (6mm ID), and third sampling the return air duct. The results of three sampling techniques lead to only a 0.06 air change/hour variation in infiltration. They also determined that sealing doors and windows near the neutral zone had little impact on infiltration.
Hittman Assoc. (1975)	1- typical house		• $INF = A + B\ \Delta T + CW$	
Elkins (1971)	2-occupied houses both have forced hot air systems; (one gas the other electric)	Tracer gas decay method using ethane	Gas house: • $INF = (A_1 - B_1\Theta)W$ $= (.095 - .0004\Theta)W$ Electric house: • $INF = (A_2 - B_2\Theta)W$ $= (.065 - .0004\theta)W$	The researchers use the tracer approach to find the relationship between infiltration and weather conditions. The data set for this project indicated that temperature was not a major factor, however, the effects of wind were more pronounced for the gas house vs. the electric house.
Howard (1966)	6 - single story detached houses	Tracer gas decay method using nitrous oxide (NO_2) Concentration measured with a infrared gas analyzer		A total of 390 measurements of infiltration were made in these houses. Half of the observations, were taken when the wall vents (located above windows) were sealed so that the effect of these vents on infiltration could be determined. The ventilators had little effect on the level of infiltration. The data indicated wind direction and chimney opens did influence infiltration; however, wind speed was found to be proportional to infiltration. The reseachers also concluded that the stack effect was apparently overridden by wind effects.
Tamura (1964)	2-single story houses both with forced hot air oil heating systems	Tracer gas decay method using helium (H_2) concentration measured with a katharometer	Wind Relationship : $\Delta P_W = A + CW^2$ A, C regression coefficients Stack Effect: $\Delta P_T \propto \Delta T^{\frac{1}{2}}$	The reseachers observed that infiltration during the summer was proportional to the wind speed while during the winter infiltration was influenced by both stack effect and furnace operations. Furthermore, the relationship between infiltration and inside-outside temperature was found to be linear with the square root of temperature. Finally, they determined that the combined effects of wind and temperature calculated separately were always greater that the level of infiltration measured.

TABLE 3 - 1 (con't)

Tracer Gas Case Studies

RESEARCHER	NUMBER AND TYPES OF HOUSES	MEASUREMENT TECHNIQUE	MODEL OR RELATIONSHIP	SUMMARY
Laschober (1964)	2-split level research houses: one house heated with a gas or electric forced air furnace while the other had a hydronic system	Tracer gas decay method using helium (He)	House #1: ● $INF = A_1+B_1\Delta T+C_1W$ House #2: ● $INF = A_2 + B_2\ \Delta T + C_2W + D_2\ EG$ Where A,B, and C are regression coefficient EG - refers to heating fuel; = 1 gas = 1 electric W-wind component striking the long side of the retangular houses	The researchers observed that using typical means for calculating the level of infiltration are always less that the level measured. Furthermore, they feel that the temperature coefficient (B) are statistically significant but that the wind coefficient (C) were not.
Bahnfleth (1951)	1 two-story research house with brick veneer (sheltered) 1-single story research house (unsheltered) Both houses used forced hot air systems	Tracer gas decay method using helium (He)	● $INF = A + B\ \Delta\ T + CW$	A detailed review of the infiltration phenomenon and indepth analysis of the data. They were some of the first researchers to address the location of the neutral zone. The researcher feel that the diffusion of helium through the walls and ceilings may have caused the measured infiltration level to exceed the actual rate. Furthermore, the researchers found that for the sheltered house that it was not possible to correlate wind direction with infiltration. However, the infiltration for a given temperature and wind situation in the summer was always less than the corresponding winter situation. Chimney effects and shielding from trees appear to account for this discrepancy.
Dick (1951)	8-two-story houses with sealed combustion (sheltered)	Tracer gas decay method using the hydrogen (H_2)	● $INF =(A_1 + B_m + Cn)\ \Delta T^{\frac{1}{2}}$ for $W^2/\Delta T < 3$ ● $INF = (A_2 + B_2m + C_2n)\ W$ $W^2/\Delta T > 3$ n = number of vent openings m = number of casement window openings	The studies by Dick, et. al are some of the most detailed infiltration research performed. One of the very interesting results of this research was the correlation between window openings and outside temperature. Since infiltration is so strongly tied to window openings, they observed a decrease in infiltration as outside temperature decreased. Note: that there is no constant term in these relationships, Dick concludes that this is because these houses have sealed combustion systems.
Dick (1949)	20-two-story semi-detached houses (unsheltered)	Tracer gas decay method using Hydrogen (H_2)	● $INF = A + Bm + Cn + (0 + E_1n + Fm)W$ n = number of vent openings m = number of casement window openings	This is one of the very few studies to address the use of windows (n for vents and m for casements) and how this affects infiltration. Dick, et. al. randomly sampled the disposition of the vents and windows to develope the relationship for infiltration. Furthermore, since some of the houses had no central heating systems, he used a network of injections and sampling tubes In this way he was able to separate air movement between rooms and true infiltration. Due to the mild climate at this location, there was no correlation between temperature and infiltration. Furthermore, he found that wind direction and humidity had little effect. Finally, they measured surface pressures and found little difference accross the structure.

information about each house was obtained. The following list represents some of the major characteristics of the structure:

- house type
- finished floor area
- heated volume
- air barrier area
- garage
- heating system type
- heating system fuel type
- domestic hot water fuel type
- type of fireplace
- chimney material

Additional information was collected but not presented in the summary report by Beach.

As with other studies using the fan pressurization technique, the rate of leakage can be modeled by the following relationship:

$$\dot{V} = K \, \Delta P^{n}$$

where

$\dot{V}$ = the volumetric flow rate

K = the value of $\dot{V}$ when $\Delta P = 1$ Pa

n = the flow coefficient

Thus it is not sufficient to express the leakage for a given differential pressure; the values of K and n must also be stipulated to completely characterize the leakage function. Since K and n often differ between houses, this leads to the result that although two houses might exhibit the same leakage at a specific ΔP, at another ΔP the houses might have different leakage rates relative to each other.

The objective of this study was to determine if a functional relationship existed between leakage and house type, (e.g. two story bungalow, split level, etc.). However, the analysis of the data indicated that the volume and barrier area of a house are not necessarily related to house type. Therefore, it was not possible to relate leakage to style of house. The researchers then used the barrier area (the area of the house which separates the conditioned space from the outside) to normalize their leakage data. Although the results were significantly better than leakage versus house type, the ratio of leakage to barrier area still exhibited some degree of variation, (approximately ± 20%). However, Beach concludes that this ratio is "the most meaningful parameter for comparing the air tightness of different houses."

Caffey (1979) recently added 20 houses to the research he performed in 1977, giving him a total of 50. The purpose of this study was to determine which building components were responsible for the air leakage. Table 3-2 summarizes the 12 major areas of leakage identified by Caffey. The leaks associated with the soleplate, electrical outlets, A/C duct system, exterior windows, and fireplace accounted for 3/4 of the total leakage. Simply caulking the soleplate, windows, and doors will greatly reduce the leakage. Installing rubber gaskets in the electrical outlets will reduce the leakage through the electrical outlets by 93%. Caffey feels that overall leakage can be decreased by 60% without expending a great deal of time or money.

As stated by Caffey, he calculates the number of air changes per hour by:

> dividing the measured [m^3/s] (leakage) air flow rate at 24.88 Pa (0.10 in. water) static pressure by 4. This number is converted to cubic [meters] per hour by using a 60 multiplier. The resultant is divided by the volume of home expressed as [m^3].
>
> What is the reasoning for dividing the total leakage by the number "4"? Under a winter design wind condition, a home is affected by a positive pressure on the windward side, a negative pressure on the leeward side, and slight positive or negative pressure on the remainder of the surfaces depending upon the wind direction and the

Table 3-2
Infiltration Test Results

Average Value for 1780 ft^2 Home

Location of Leak	Leakage per Item (ft^3 /min /unit)	Number of units	Total Leakage	Percent of total	Cummulative
Soleplate	3.6/ln ft crack	175 ln ft crack	630	24.6	24.6
Electrical wall outlets	8/outlet	65 outlets	570	20.3	44.9
A/C duct system	345/system	1 system	345	13.5	58.4
Exterior Window	23/window	13 windows	300	11.8	70.2
Fireplace	139/fireplace	1 fireplace	139	5.5	75.7
Range Vent	132/range vent	1 range vent	132	5.2	80.9
Recessed Spot Light	33/light	4 lights	132	5.2	86.1
Exterior door	39/door	3 doors	117	4.6	90.7
Dryer Vent	71/dryer vent	1 dryer vent	71	2.8	93.5
Sliding Glass Door	43/door	1 door	43	1.7	95.2
Bath Vent	33/bath vent	1 bath vent	33	1.3	96.5
Other			96	3.5	100.0
			2,558		

Source: Caffey (1979)

> physical shape of the home. Tested on pier and beam,U-shaped construction seemed to indicate a number in the order of 4.5 would be necessary in order to correlate with previously assumed air infiltration data. Tests in conjunction with gas tracer devices indicated the number 3.5 for single-story, slab construction. The number 4 is used to represent a broad spectrum of home designs in the 50 home test sample.

Thus, Caffey uses this technique to represent the physical forces exerted on the house under typical weather conditions.

A similar study was performed by Tamura (1975). Again, the object of this research was to determine the major areas of the house where air leaks occur. Tamura used the fan pressurization technique to measure the leakage in 6 detached houses (four bungalows and two two-story) with forced hot air systems. Prior to each test, the outside surface of the walls, floor, windows, doors, vents, fireplace, and chimney openings, etc. were sealed. The house was then pressurized and the seals were removed one at a time. All leakage measurements were made at 75 Pa (0.3 in. of water); leakage rates were not obtained for other pressure differentials. The results of the research are summarized in Table 3-3. Note that the brick houses leak through or around the outer walls while the major leaks for the stucco houses were through or around the ceiling. Furthermore, the leakage through the door/windows accounted for approximately 20-25% of the total.

In addition to the research projects highlighted here, there have been a few other studies concerning leakage performed in the past. The significant results of each project are summarized in Table 3-4.

3.3 Case Studies Concerning Both Infiltration and Leakage

In 1979 three studies were released which attempted to establish a relationshp between the level of infiltration obtained from

Table 3-3

Total Leakage Rates of Typical Houses

House Type/ Exterior Finish of House	Total Leakage $\dot{V}$ @ $\Delta P=75$ Pa	Percentage Lost		
		Ceiling	Outerwalls	Doors/Windows
One story stucco	1160	65	16	20
One story stucco	1100	57	21	22
One story brick	2410	16	65	19
One story brick	2620	34	42	24
Two story brick	2170	8	77	15
Two story brick	2240	11	66	23

Source: Tamura (1975)

Table 3-4

Fan Pressurization Case Studies

RESEARCHER	NUMBER OF TYPE OF HOUSE	MEASUREMENT TECHNIQUE	MODEL OR RELATIONSHIP	SUMMARY
Beach (1979)	Total of 67 houses tested • 38 two-story houses • 12 bungalows • 11 split-level • 4 HUDAC houses • 2 1½-story houses	Fan pressurization	Leakage $\dot{V} = K(\Delta P)^n$ and ($\dot{V}$ @ ΔP = 10Pa)/(Barrier Area) = Const. = $.785 \times 10^{-3} \pm .165 \times 10^{-3}$ Infiltration = leakage/house volume	The study was restricted to new houses built in 1978. Several types of houses, built by 9 different builders were selected for the study. The rate of leakage was measured at several differential pressures. This allowed the determination of K and n for each house. They defined the Relative Tightness to be the ratio of the volume rate of air flow ($\dot{V}$) at 10Pa and the Barrier Area. The intent was to find a relationship between leakage and house type but due to the variation in houses within each type, the relationship was not very strong. However the relationship between leakage and barrier area appears statistically more significant. Furthermore, they conclude that each builder produces houses within range of relative tightness values.
Caffey (1959)	Total of 50 houses tested. Detailed breakdown of the house types were not available.	Fan depressurization	Air Change/hr $= \frac{\text{Discharge volume}}{\text{Volume of House}}$ Discharge volume $= \frac{\text{Leakage @ 62.2 Pa}}{4}$ The number 4 is used to reduce the leakage to represent the effects of wind blowing on one side of the house.	The "super sucker" was installed in a window and used to depressurize the house. The objective of the study was to quantify the various components of a house which allow infiltration to occur. The tests were run at 62.2 Pa (.25 in. of water). They found that leakage through the soleplate (24.6%), electrical outlets (20.3%), A/C duct system (13.5%), windows (11.8%), and fireplace (5.5%) accounted for 75% of the leakage. They conclude that relatively inexpensive retrofits could reduce leakage by 60%.
Collins (1979)	A total of 59 houses were tested, however, only the results of the 29 houses that were retrofitted are reported. • 15 Ranch • 7 Tri-level • 4 Bi-level • 3 Two-Story	Fan depressurization	Leakage $\dot{V} = K(\Delta P)^n$ Infiltration = leakage/house volume	The fan depressurization technique was used to measure the leakage before and after retrofits were performed. The leakage test were conducted at 25Pa (.1 in. of water) pressure differences. The reduction in leakage ranged from 39% for the tri-levels to 13% for the bi-levels.
Treado (m.d.)	1 house was tested; a 3 bedroom townhouse with gas forced air heating system, slab on grade construction.	Fan pressurization		The test house was evaluated during two different operating conditions; winter and summer. The fan pressurization technique was used to measure leakage for the entire house and with various components sealed. The results indicate that during the winter the furnace fan, combustion air intake, and dilution air account for 30% of leakage.
Kronvall (1978)	29 houses were tested. • 17 1½-story • 10 one-story • 2 two-story	Fan pressurization		The level of leakage was determined at 50Pa and compared to the level allowed by Swedish law--only 9 of the houses had less than the 3.0 air changes per hour at ΔP = 50Pa as prescribed by the law. The ratio between leakage:volume and leakage:envelope were calculated. Both ratio exhibited a large variation. However, a relationship between the ratio of leakage:envelope area and the level of infiltration were established: $INF = 0.03\ (\dot{V}/Area)^{1.1}$ Where $\dot{V}$/Area is evaluated at 50Pa and INF determined at low wind speeds.
Tamura (1975)	6 houses • 4 bungalows • 2 two-stories	Fan pressurization		The objective was to measure the leakage through various building components. The researchers found that the four brick houses tended to leak through the outer walls while the major leak for the stucco house was through the ceiling. Furthermore, the amount of leakage through the doors/windows accounted for approximately 20-25% of the total.

a tracer gas study with the rate of leakage determined with a fan pressurization test such that leakage is reported for a specific pressure differential. However, due to the physical relationship between wind, temperature, and infiltration it is often difficult to standardize the infiltration results to a specific wind/temperature condition without extensive field tests. The importance of such a relationship can not be overemphasized: an infiltration measurement can be used to estimate the amount of energy lost while leakage measurements determined, at 50 Pa. for example, do not have a direct bearing on energy losses under natural conditions. Therefore, a relationship of this sort would be very useful in energy loss calculation.

Blomsterberg (1979a and 1979b) and Grimsrud (1979) both approached the problem in a similar fashion. Their predictive model is based on two inputs; first, the measured air leakage rate at a specific pressure differential, and second the pressure distribution over the exterior of the envelope. The first input can be easily obtained via fan pressurization. However, the pressure distribution is a more complex natural phenomenon and, therefore, more difficult to quantify. One approach is to obtain local weather data and adjust the wind speed and direction for the terrain immediately surrounding the test house. A second approach is to actually measure the surface pressures on the exterior of the envelope. These surface pressures can be measured using a network of plastic tubes which are connected to a manifold equipped with a sensitive pressure transducer. The real value of the network approach will probably be to benchmark the model used to obtain local surface pressures from the weather station wind data. Modeling the movement of wind

Actual
Pressure
Measurements
vs
[illegible]

across a landscape dotted with buildings is a complex problem. Thus, the problems associated with determining the relationship between leakage and infiltration are significant though not necessarily insurmountable. However, a great deal of data pertaining to infiltration as a function of weather conditions, leakage at low pressures, wind effects on structures, and extrapolation of weather station wind data to the test house is required to establish this relationship.

4.0 TECHNIQUES FOR DETECTING AND REDUCING AIR INFILTRATION IN NEW AND EXISTING HOUSES

Builders and occupants of residential structures are faced with the problem of excessive infiltration of outside air. Their task is, therefore, to reduce or alleviate the unwanted infiltration. For the residential occupant this is a two-stage process: first the location of the air infiltration leaks must be detected and second some type of corrective action must be taken. The task for builders is somewhat different in that they must construct the house in such a way as to reduce the level of infiltration.

The review of the literature revealed a number of detection techniques for locating major and minor air leaks in existing houses. Each method has advantages and disadvantages. For example, some of these techniques can be quite costly, requiring sophisticated equipment (e.g. thermography) or relatively inexpensive, requiring little or no equipment (e.g. tracing the flow of air with smoke sticks). Furthermore, the success of each method is not necessarily a direct function of the cost and sophistication of the equipment but may be related to the person conducting the infiltration detection test. Although all of the common detection methods are based on scientific fact, interpretation of the results is the major factor bearing on the successful identification of the major air leaks.

Several research projects were specifically designed to quantify the savings obtained from various types of retrofit. The results of these research projects indicate that the most cost-effective infiltration retrofits are caulking and weatherstripping although several other possibilities exist.

As energy prices increase, the designer and builder of residential structures have sought to improve their thermal integrity. Air infiltration was recognized as an area where significant energy savings could be obtained through thoughtful design and careful construction. As a result of these efforts, several innovative approaches for reducing infiltration have emerged. It has become apparent through these new designs that a wholistic approach must be applied to the infiltration problem.

The first two sections of this chapter will discuss the various detection methods available to locate infiltration problems and the existing retrofit techniques which can be used to reduce the unwanted influx of air. The final section of this chapter will present a few of the more successful housing designs which have drastically reduced the rate of infiltration.

4.1 Methods for Detecting Air Infiltration

There are several diagnostic techniques for finding the numerous air leaks present in existing houses. The following list constitutes the principal detection methods:

- infrared thermography (with and without fan pressurization)
- tracer gas
- fan pressurization (whole house or component)
- transmission of sound
- visual inspection for cracks

Infrared thermography and the use of tracer gases require expensive equipment and often extensive laboratory facilities to analyze the results. The remaining three methods are relatively inexpensive, straightforward, and require little time or experience. Since the physical principles for each of these techniques has already been discussed at length in Chapter 2 of this report only the operational aspects of each detection method will be presented here.

Infrared thermography is an expensive technique and requires a trained operator to perform the analysis. This method is often coupled with the fan pressurization (depressurization) technique to accentuate the exchange of air between inside and outside. The use of thermography represents an excellent qualitative tool for identifying the location of air leaks. However, due to the nature of thermography it is impossible to quantify the level of infiltration.

To locate the air infiltration passageways, several infrared pictures are taken of the house being analyzed. For best results this method should be employed on days when there is a significant difference between the indoor and outdoor temperature. This will ensure the adequate transfer of air (heat) and produce the greatest contrast on the infrared picture. These pictures can then be analyzed to determine where the air leaks are located. In general, pictures of the windows, doors, exhaust fan outlets, flue ways, electrical outlets, and the joints between the foundation/wall and wall/ceiling are the regions to be considered carefully.

The thermography approach can be coupled with the fan pressurization technique. This increases the cost of the detection process but adds a quantitative component to the anlaysis. Depending on the orientation of the fan, the house will be pressurized or depressurized. Typically, the best results are obtained when the house is depressurized causing the outside colder air to flow into the house. The fan should be operated at a standard pressure differential (e.g. 50 Pa. or 0.2 inches of water) so that the effectiveness of the retrofit performed can be evaluated.

One advantage of this approach is that the leaks can often be blocked while the thermography scan is being performed. However, the primary disadvantage is the cost of a thermography scan ($40-50 for each side of the house). The benefit of this approach increases as the tightness of the house increases since it becomes increasingly difficult to locate the remaining air passage ways. Thus as new houses are built tighter the use of thermography to evaluate the thermal integrity of the structure may increase.

The use of tracer gas as a detection technique yields the most precise quantitative information about the level of infiltration. However, it is much more difficult in general to implement this approach and almost impossible to determine the location of the air leaks. Furthermore, the cost of this method ranges from being quite expensive if continuous monitoring is performed to being relatively cost-free when bag samples are taken. Since the absolute level of infiltration is dependent on such factors as current wind conditions and inside-outside temperature differences a great deal of variation may occur between sample times and houses. Thus, it is not always possible to qualitatively evaluate the effectiveness of the retrofit performed unless extensive tracer gas data is available over a broad range of wind and temperature conditions. Therefore, the tracer gas approach is seldom used for the purpose of <u>locating</u> air leaks. It is, however, a powerful experimental tool and its value should not be underestimated.

The fan pressurization (depressurization) technique has been applied with great success in identifying major and minor air leak passages. This approach can be applied at the whole house level or at the level of specific components such as windows or doors. It must be noted that with this approach it is impossible to estimate the level of air infiltration in terms of air changes per hour. However, it is possible to evaluate the effectiveness of any retrofit performed.

If this approach is applied to the entire house, a fan pressurization door unit is used to create a pressure differential between the inside and outside. In general, it does not matter whether the fan is operated so as to increase or decrease the pressure within the house. In either mode of operation the person conducting the test can simply pass a smoke stick near the edge of the windows, doors, electrical outlets, etc. and observe the movement of the smoke. If the fan is pressurizing the house the smoke will flow out through any crack in the envelope. In general, it is most efficient to mark the location of the leak and then to proceed. The Lawrence Berkeley Laboratory has prepared a pamphlet that describes how this process can be accomplished by the occupant with a reasonable small dollar expenditure.

Infiltration can occur as a result of simple or complex air passageways. A simple path might be a crack around a window which allows air to pass into the house directly. An example of a complex path is when air enters near the foundation and flows through the wall cavity and finally enters the house through a ceiling light fixture. Thus, the use of the fan pressurization technique is useful in locating leakage points but it cannot differentiate between simple and complex flow paths. Therefore, when using the fan pressurization technique it is most effective when leaks are identified on the inside solidifies and forms a thin transparent film. According to the manufacturer, this film can be easily applied in the fall of each year and then removed during the spring. To date there have been no field studies to evaluate the performance of this particular product. However, it is suspected that if the air leaks are not too severe this spray caulk may prove satisfactory for reducing air infiltration. Except for the example sited above, the review of the literature did not reveal any other product improvements related to caulking and weatherstripping. Discussions with home improvements contractors indicated that to caulk and weatherstrip a typical window would cost approximately $40 for materials and labor and take 1-2 hours. The homeowner could, however, purchase the materials for approximately $6-8 and perform the work himself.

The next retrofit measure which can be applied with relative ease is the installation of foam gaskets in every electrical outlet. The installation is quite simple: remove the cover plate; insert the gasket; replace the plate. This is an excellent way to reduce the flow of unwanted air through complex infiltration paths. A recent study performed by Caffey (1979) indicated that 20 percent of infiltration occurred as a result of air flow through electrical outlets. Caffey found that the foam gaskets decreased the rate of leakage by 93 percent.

The next set of infiltration retrofits requires considerably more time and money (e. g., install storm windows and doors. In addition to reducing infiltration (assuming the windows and doors are caulked and weatherstripped correctly) the new doors and windows reduce conductive heat transfer.

and on the outside of the structure. The external inspection should concentrate on the structure interfaces (e.g. foundation/wall, wall/ ceiling, corners, etc.) and at points where the exterior envelope has been penetrated (e.g. plumbing fixtures, external electrical outlets, chimneys, exhaust fans, etc.).

The next detection method of concern uses sound to locate the openings which allow the flow of air into the house. This method requires limited equipment and can be performed by the occupant. However, it should be noted that this method does require some time to become proficient at locating and identifying the leak. Field research performed by Bolt, Beranek and Newman, Inc. indicated that near corners and other structural component interfaces care must be exercised in interpreting the results. For instance, where two structural components are joined, up to a 3dB increase in the sound can be observed even though no leak is present. Furthermore, in a corner the sound might increase as much as 6dB again with no apparent air leak. The increase in sound is a result of the reflection of the sound waves. However, if an air leak is present the sound level increases by 10dB. Thus, the person using this approach should always compare the sound level in corners suspected of having air leaks with a corner of similar configurations known to have no leaks.

The final air infiltration detection technique is the visual inspection of the structure. This technique has been used for years to try to locate the apparent air passages which allow air to flow into the house. Due to the complex movement of air it is not always possible to locate the penetration in the envelope causing the major air leaks using visual inspection. However, the primary advantage of this approach is the ease with which it can be performed;

therefore it should preceed use of any of the other detection methods. It is possible to locate and repair several of the major leaks with a very limited expenditure of time and money using this method.

Once the air leaks have been identified by any of the detection methods it is then necessary to take corrective action to reduce the flow of air. The various techniques and materials required to block the air passageways will be discussed in the next section.

4.2 Methods for Reducing Air Infiltration in Existing Houses

The techniques or methods available for reducing air infiltration fall into two categories. The first consists of caulking, weatherstripping, and installation of gaskets. This group of retrofits is typically inexpensive and easy to install. The second group usually requires the assistance of a home improvement contractor (e.g. storm windows, stack dampers, insulation) and is generally more costly. Each of these retrofit techniques helps reduce the level of infiltration and some also improve the thermal integrity of the structure as well. Each approach will be briefly discussed in this section.

The principal method for reducing the inflow of outside air is to caulk the holes or cracks causing the problem and to use weatherstripping on doors and windows to improve the existing seal. The time to perform the retrofit depends on the number, type, and location of the air leaks. In addition to the common materials used for caulking which are available today, one generically new product has appeared on the market: a spray can filled with a liquid plastic. When this material is sprayed onto a window/wall seam the plastic

If the house does not have sufficient insulation, it can be added under certain circumstances. The addition of insulation helps to block the flow of air within structural cavities and therefore reduces the rate of infiltration. A final retrofit which can reduce the rate of infiltration is the installation of a stack damper (applicable only to fossil fuel heating systems). Stack dampers restrict the flow of air up the flue when the heating system is not in use.

Several recent research projects have been performed specifically to evaluate the effectiveness of air infiltration retrofits. Most of these studies evaluated a group of retrofits rather than specific retrofit measures. For instance, John Collins (1979) directed an extensive retrofit study on 59 electrically heated homes in the Denver, Colorado area. Their general retrofit package consisted of the following:

- fiberglass the inside of all exterior walls being careful to seal around windows, doors, electrical outlets, and interior partition walls.
- caulk and weatherstrip doors, windows, and seams between structural components.
- installation of foam gaskets in the electrical outlets.

The fan pressurization technique was used to locate the various air leaks and also to evaluate the effectiveness of the retrofit package. To insure comparable results they always maintained a pressure differential of 25 Pa (0.1 inches of water). The researchers first measured the initial leakage rate, then retrofitted the house and measured the new leakage rate. They found the following structural features to be the principal sources of air infiltration in at least 50 percent of the houses in the study:

bottom of drywall
window fit (including sill)
plumbing fixtures (inside and outside walls)
electric fixtures
bathroom vents
outside door fit
access to attic space

The retrofits performed in this study were estimated to cost approximately $1000 for labor and materials (1979 dollars) and they reduced the level of leakage by 30 percent. It is interesting to note that even with this reduction in leakage, only three of the test homes would comply with the Swedish Standard (i.e. at 50 Pa. the leakage must be less than 3.0 air changes per hour).

Another study directed by D.T. Harrje on 30 townhouses located in Twin Rivers, New Jersey evaluated the effectiveness of several retrofit measures. He found that energy savings could amount to 25 percent and that infiltration could be reduced by 35 percent. The fan pressurization technique coupled with infrared thermography was used to identify the location of infiltration sources and to quantify the improvements obtained from the retrofits. He feels that the major infiltration sources are the following:

- the lack of squareness of the window frames
- the poor condition of the seal between the glass and the window frame
- the air channels that allow air to flow past the molding strips.

Caulking and weatherstripping were the most common retrofit measures to obtain the decrease in infiltration.

To quantify the amount of energy saved as a result of retrofits Harrje developed the "energy signature" of the house. The energy signature is a graphic representation of the amount of fuel consumed as a function of outside temperature. Thus, by knowing the rate of fuel consumption and the outside temperature this graph can be produced (see Figure 4-1 for an example of a typical energy signature). It is then possible to use this graph to measure the energy savings that result from a variety of energy related retrofits. A decrease in energy consumption will decrease the slope of the line while a decrease in the inside temperature setting will displace the graph to the left with no change in slope.

The results obtained in these studies have been substantiated by many other researchers. Furthermore, the type of retrofit and the reduction in infiltration tend to be of the same order of magnitude. Most studies used fan pressurization to evaluate the effectiveness of the retrofit measures. The main advantage of this approach is that the leakage function of the house can be measured without occupant behavior affecting the results. This enables a clear comparison between the before and after situation.

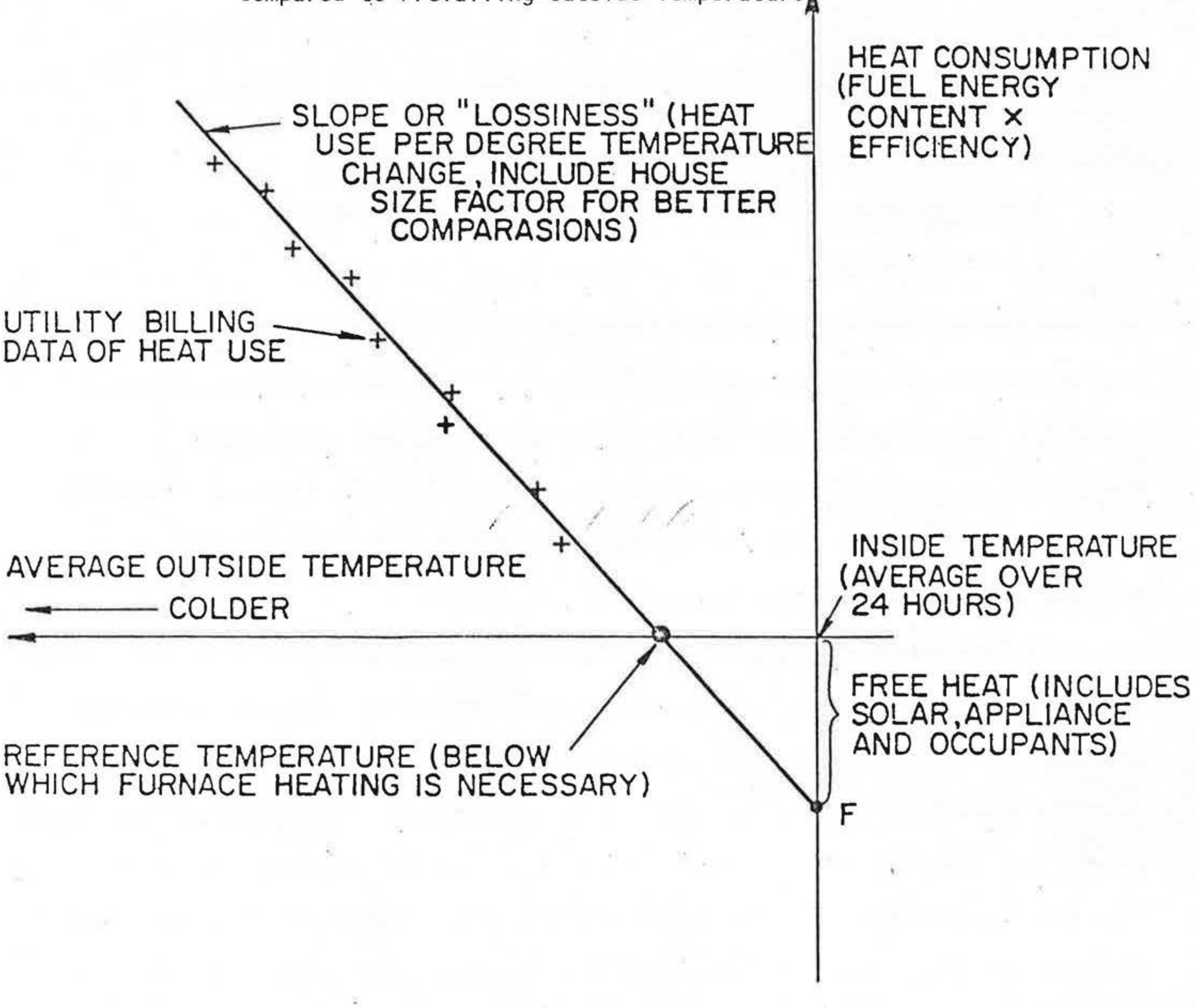
4.3 Design and Construction Details for Reducing Residential Air Infiltration

As energy prices have increased the architect and builder of residential structures have reviewed all facets of the design and construction process to determine how houses can be made more energy efficient. For years it has been well understood that reductions in air infiltration would save substantial energy. Furthermore, the changes required in the initial design or during construction to decrease the level of infiltration would not be that significant.

In recent years several so-called energy efficient houses have been built in the United States, Canada, and Europe. Although

Figure 4-1

"Energy Signature" of the House, Where Heat Consumption is Compared to Prevailing Outside Temperature



Source: Harrje (1979).

the specific design of each house is different, the overall objectives of reducing energy consumption and decreasing the inflow of outside air have been accomplished. The major design changes generally incorporated into an energy efficient house are as follows:

- design/construction details
- equipment additions, changes, or improvements
- landscaping

The review of the literature has revealed two houses which exemplify the three design categories listed here: the Saskatchewan House, built in Saskatoon, Saskatchewan, Canada; and the Arkansas House built in Little Rock, Arkansas. Each of the three categories will be discussed using the Saskatchewan and Arkansas houses as examples where appropriate.

Before proceeding with the detailed discussion of the new design approaches for reducing air infiltration it is necessary to review the general construction details of each house. First, consider the Saskatchewan House--it has also been called the super insulation house since the R-value of the roof equals 60, the R-value of the wall equals 39, and the R-value of the floor equals 27. The most distinguishing feature of this house is the dual wall construction; the inner and outer walls consist of 2" x 4" studs placed 24" on center. An insulation gap separates the inner and outer wall making the total wall thickness equal to 12 inches. The vertical gaps in each of the framed walls are filled with 3½" of fiberglass batting while the insulation gap is filled with two layers of horizontal 3½" batting insulation to alleviate the flow of air at seams. The Arkansas House on the other hand uses 2" x 6" studs placed 24" on-center with the wall gaps filled with 6" fiberglass batts. Furthermore, the Arkansas House uses a special corner construction to alleviate the insulation void normally present in typical wall designs.

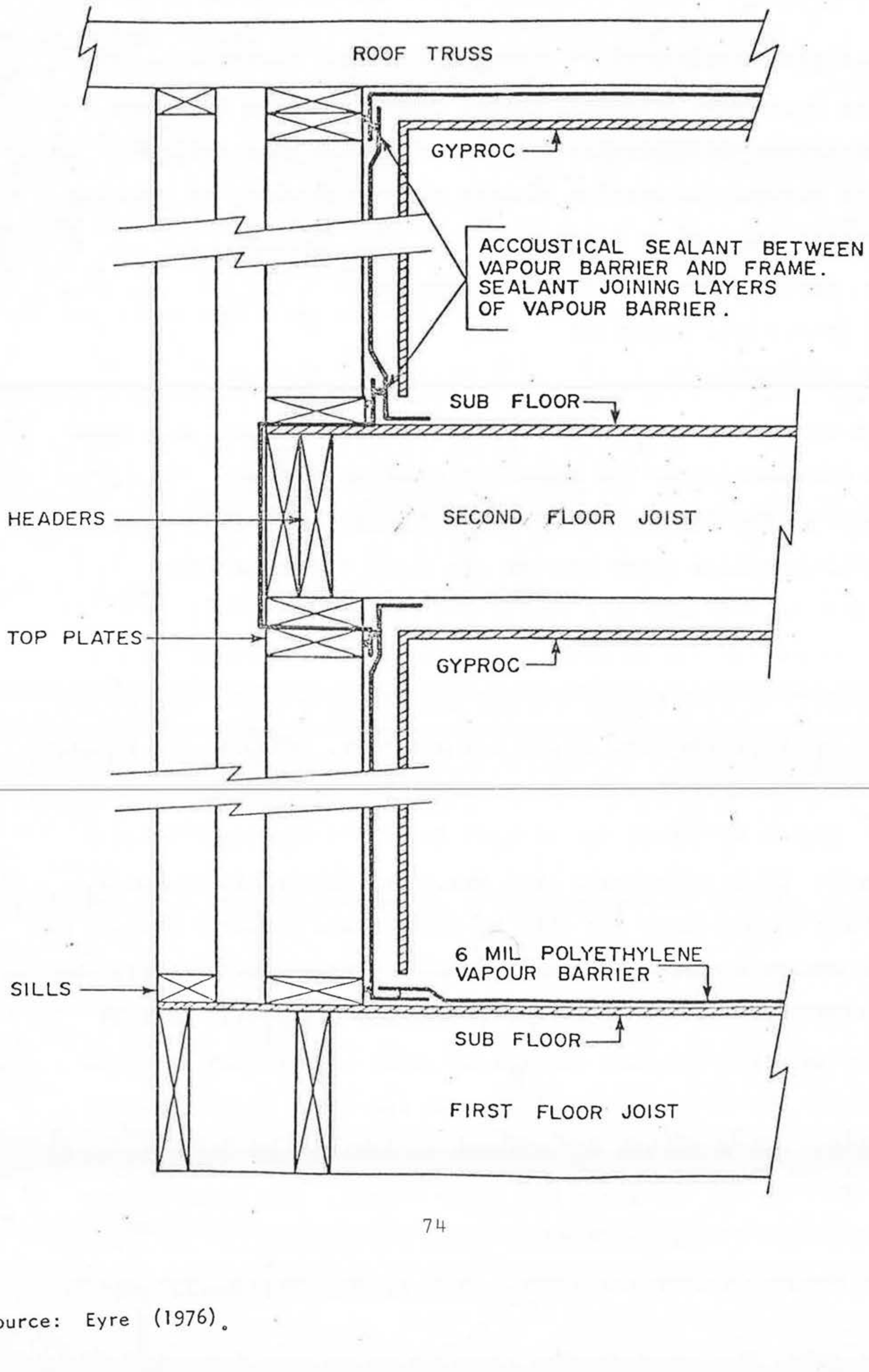
The design/construction details related directly to reducing air infiltration are as follows:

- special vapor/infiltration barriers
- structural interface
- windows

In both the Saskatchewan and Arkansas houses great care was taken in the installation of the vapor/infiltration barrier. The designers of the Sasketchewan house recognized the importance of a well-installed vapor barrier and noted that "the ideal vapor barrier consists of a completely sealed polyethylene bag enclosing the living space, with openings for windows and doors only." In both houses a 6 mil polyethylene vapor barrier was used to restrict the flow of air and moisture. Figures 4-2 through 4-5 depict the installation of the vapor barrier in the Saskatachewan house. Figure 4-2 shows the overall detail of the vapor barrier placement. It is noteworthy that the vapor barrier is passed around the second floor and that an overlap and acoustic sealant is used to ensure a continuous vapor barrier. Figure 4-3 details the installation of the vapor barrier around the electrical outlets and shows how the PolyRama electrical vapor pan is used. Figure 4-4 details the special installation of the vapor barrier around vent pipes. Note the use of caulking to seal around the pipe as it passes through the top plate and floor joists. The final figure in this series (Figure 4-5) details the installation of the vapor barrier around windows and doors. Once again, caulking is used to

Figure 4-2

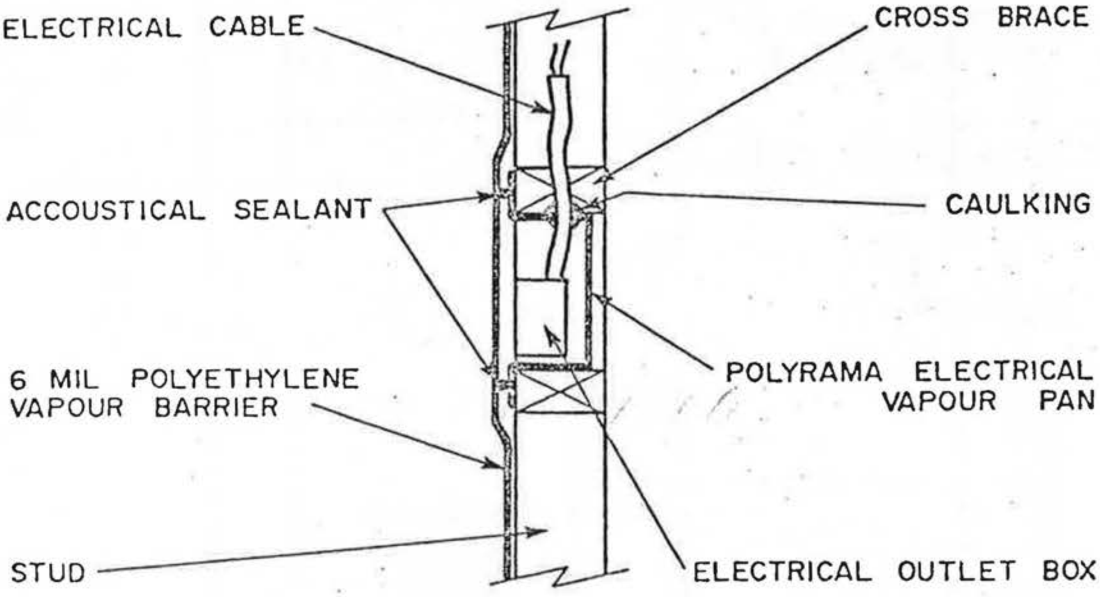
Vapour Barrier Installation (Schematic)



Source: Eyre (1976).

Figure 4-3

Vapour Barrier Installation
Around Electrical Fittings.



Source: Eyre (1976).

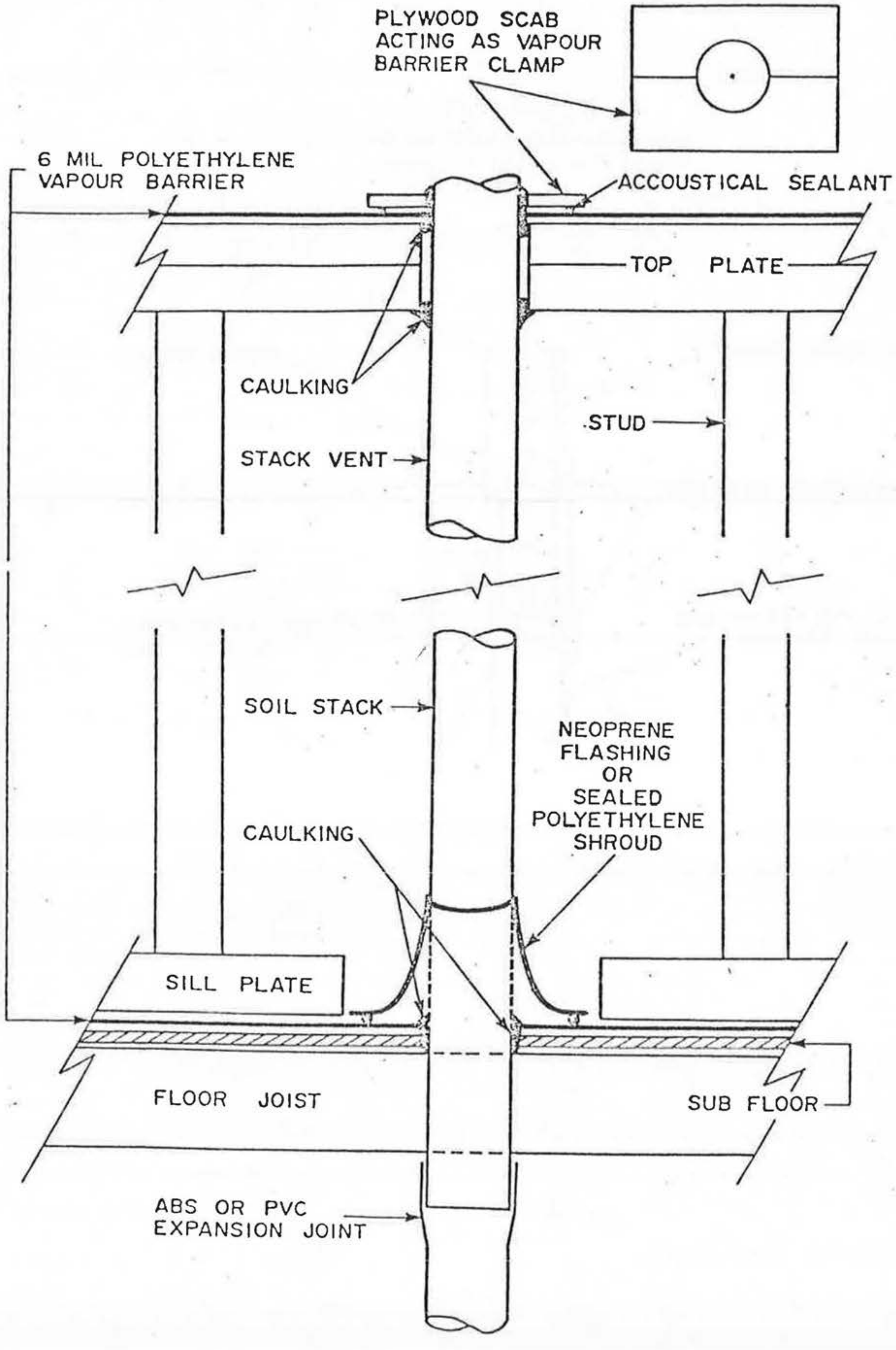
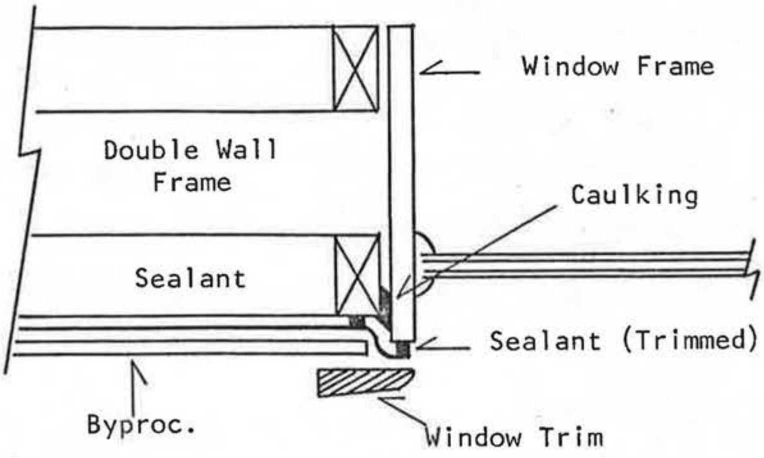


Figure 4-4

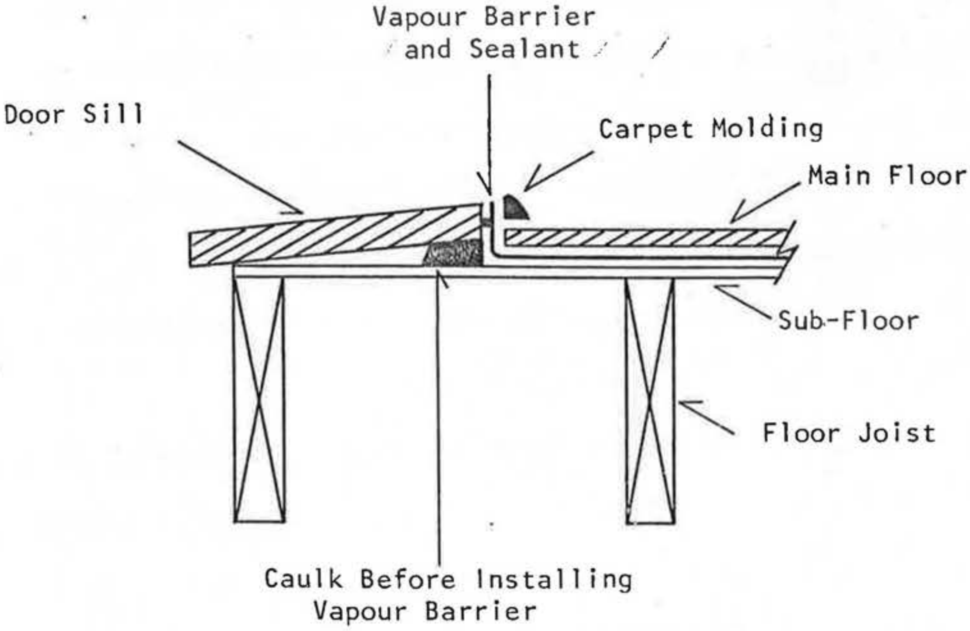
Vapour Barrier Installation
Around Vent and Soil Stacks.

Source: Eyre (1976).

Figure 4-5



Vapour Barrier Installation Around Window (Schematic)



Vapour Barrier Installation Around A Door (Schematic)

Source: Eyre (1976).

to improve the effectiveness of the vapor barrier. These figures demonstrate that a great deal of care and time was devoted to the installation of the vapor barrier. The overall infiltration rate for the Sasketchewan house is approximately 0.2 air changes per hour and the designers believe that the vapor barrier is a major feature in reducing the rate of air infiltration. Thus, in future residential construction vapor barrier installation will be done with much greater care.

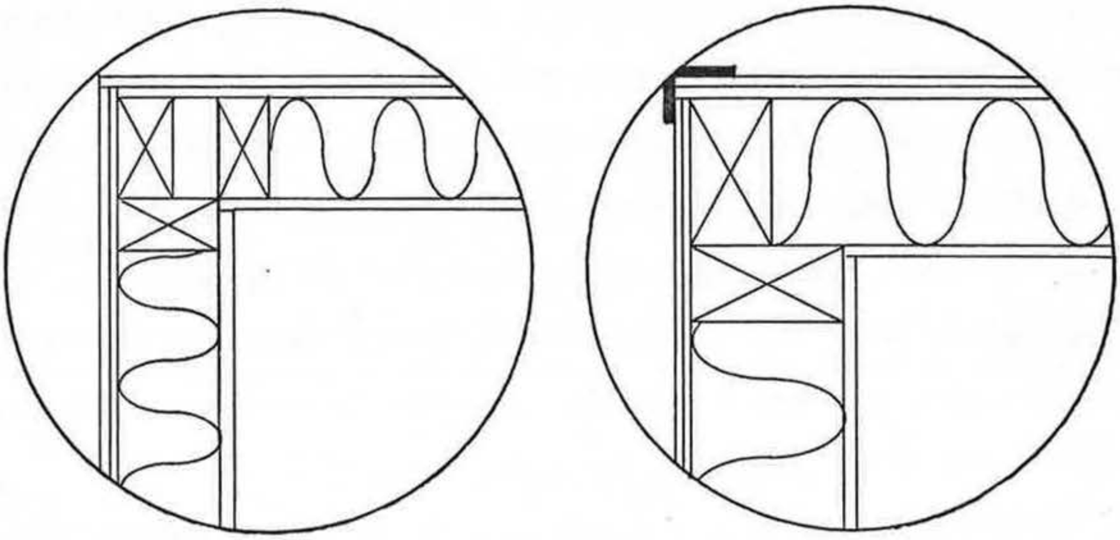
The next major design characteristic which helps to reduce air infiltration concerns the structural component interfaces (e.g., floor to wall or the interface between an interior partition wall and an exterior wall). To obtain a better seal between the floor/wall or wall/ceiling interface a bead of caulk is made along the bottom of the sill and the top side of the top plate. When the wall is connected to the floor or ceiling a flexible gasket is formed by the caulk to seal the structure from any air movement. Another design detail used in the construction of the Arkansas house is shown in Figure 4-6. The two construction details of interest are the corner and wall interface. In the Arkansas design there are no insulation gaps. In typical construction, gaps in the walls allow the free, unobstructed flow of air within the wall cavity and can be a major source of air infiltration.

The final air infiltration related design/construction detail concerns the selection and installation of the windows. In the Saskatchewan house most of the windows were non-operable to reduce infiltration by eliminating the window seals which can deteriorate with time and allow air to pass.

The next major operational change that will become more universal

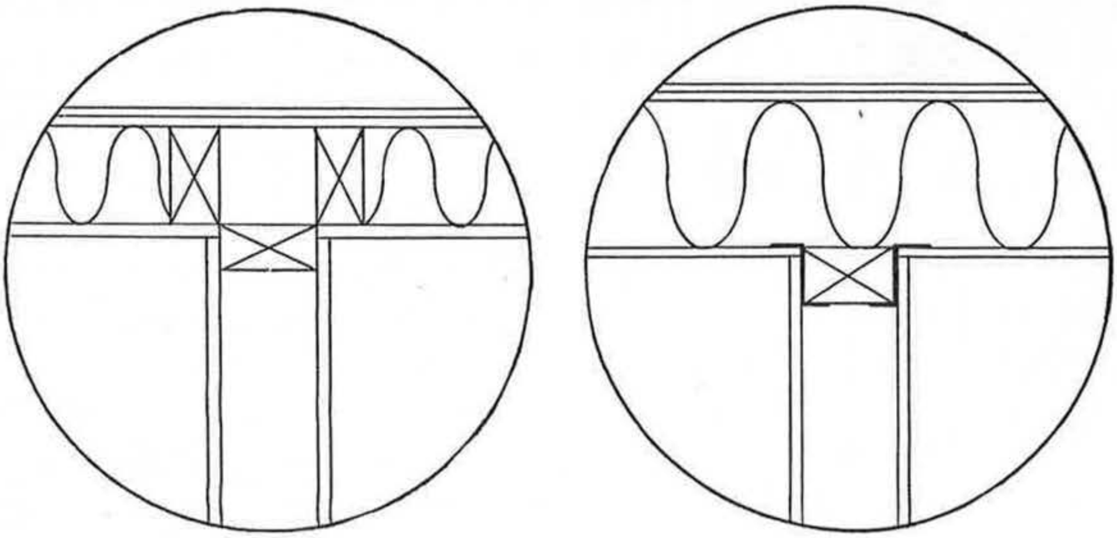
Figure 4-6

Arkansas House Framing Methods
Compared to Typical Construction



Typical Corner
Construction

Arkansas House
Corner Construction



Typical Partition
Wall Construction

Arkansas House Partition
Wall Construction

in the future is the use of sealed combustion heating systems and air-to-air recuperators. In the past sealed combustion sytems have not been used extensively, but the use of such units will become increasingly more important as the housing stock tightens up. In addition, since future houses will be significantly tighter, air-to-air heat exchangers may be required to maintain the quality of the indoor air. Currently, the Lawrence Berkeley Laboratory is conducting a study on several air-to-air heat exchangers to determine typical operating characteristics.

The final category concerns site preparation or landscaping to minimize the impact of prevailing winds. Since wind is one of the major driving forces of infiltration, it is helpful to place non-deciduous trees along the side of the house that faces the prevailing winds. Furthermore, trees can be used to shade the house during certain times of the year, thus reducing the temperature differential between the inside and outside of the house.

5.0 OCCUPANT EFFECTS ON AIR CHANGE RATES

In this chapter, we will review the literature on how occupants affect the total air change rate in buildings. We will examine the factors that determine occupants' use of ventilation (both natural and mechanical), and the factors that indirectly influence occupant impacts on infiltration rates. Our review makes it apparent that additional research needs to be done to comprehensively assess these factors.

The use of precise and consistent terminology in this area is important because the development of standardized application of these terms is still an on-going process. The following are the definitions of infiltration, ventilation, and total air change rates used in this chapter.

- Infiltration: The uncontrolled leakage of air through cracks and other openings in the building envelope.
- Ventilation: The process of supplying or removing air in a building which is controlled by the occupant through either natural means (opening windows and doors), or mechanical means (operating exhaust fans and vents).
- Total air change rate: The sum of all infiltration and ventilation processes.

Thus, when occupants open windows or doors, they are directly controlling the ventilation rate (and therefore the total air-change rate) of a building. In like manner, when occupants improve the air tightness of the building envelope through retrofit measures, they are directly controlling the infiltration rate.

However, it is also possible for occupants to affect the infiltration rate without directly intending to do so. The phrase "occupant effect on infiltration rates" can be reserved for this situation. For example, when occupants adjust their thermostats (changing the difference between indoor and outdoor temperature), they alter the stack pressure, which influences infiltration.

Field studies have shown that air exchange may represent between 20-50 percent of a building's heating load (LBL 1978). In a study of residential energy consumption at Twin Rivers, Harrje, Socolow, and Sonderegger (1977) have shown that energy consumption by households in very similar housing units can vary by a factor of 2. Furthermore, Socolow (1977) determined that 46 percent of the variation in energy used for space heating can be attributed directly to occupant behavior. In sum, heating losses due to air changes are very large and occupant-related effects account for a large share of the total loss. Furthermore, occupants vary greatly in their energy consumption patterns.

LBL (1978) suggests three general categories for classifying occupant effects on the total air change rate in a building:

- Opening windows and doors
- Operating exhaust fans and vents
- Operating the heating system

Most research has concentrated on the first of these areas.

These areas do not involve permanent physical changes that an occupant might make to the building envelope itself, but rather reflect usage patterns. Thus, a fourth category mentioned in the literature might be included for the sake of completeness:

- Occupant installation of infiltration reduction measures

Since infiltration reduction measures were discussed in detail in the previous chapter they will not be discussed further here. The relevant literature in the areas of natural ventilation, mechanical ventilation and heating system effects are discussed in turn in the following sections.

Natural Ventilation Effects

As LBL (1978) points out, the most important contribution to the total air change rate is the effect of open windows. It should be noted that opening windows just a small amount, can increase the number of air changes by orders of magnitude. While this issue is not well understood yet, a few results are available.

Brundrett and Hartmann (DOE 1979) show that the air change rate of a room is multiplied by a factor of 2 to 5 when one window is opened by only a few centimeters. A completely open window increases the air change rate by a factor of 10 to 30.

For Instance, Bergetzi, Hartmann et al. (LBL 1978) measured the following average values for casement windows:

Closed window	0.15 air changes per hour
1 window, open 10 cm	2.50 air changes per hour
1 window, open 45°	6.00 air changes per hour
1 window, completely open	7.50 air changes per hour

The air change rates from open windows are highly variable, due to the complex interaction of many factors, including wind speed, direction, and turbulence; interior air chamber effects, and outside temperature. To better understand how these and other factors combine to produce high air change rates requires further research.

Newman and Day (1975) have compiled data on the window opening habits of American households which they derived from survey research on general energy consumption (Table 5-1). Although there may be several effects contributing to these results, they tend to indicate that American households exhibit an awareness of the increased energy costs of ventilation since the number of households with open windows at night decreases both when heating degree days increase and when occupants pay directly for space heading (line a.) It also appears that households recognize the increased energy costs of not closing the "room door" when windows are left open at night (line c.) .

IEA (1979) points out that the research on how occupants affect air change rates by opening windows has for the most part taken place in Europe, which is largely a result of differences in North American and European building stocks.

North American stock includes a large percentage of normally closed buildings having central forced-air heating systems, whereas European buildings include many structures with steam or water radiant heating units which are near operable windows. Care must be exercised in applying European research on occupant effects to North American problems because of these construction differences and also the following considerations:

- Energy prices have long been much higher in Europe, producing much stronger motivations to conserve energy;
- Climate characteristics vary from region to region.

The first researchers to address the effects of occupant window opening behavior on the air change rate of dwellings were Dick and Thomas (1951).[1] Infiltration rates of 20 closed homes at Abbot Langley were compared with total air change rates while

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[1] The application of this research to infiltration measurement has been discussed in Chapter 3.0.

Table 5-1

American Window Opening Habits

	All Households	Heating Degree Days			Pay for Space Heat	
		<3500	3500 5499	>5500	Yes	No
All households	100%	100 %	100 %	100 %	100 %	100 %
a. Windows sometimes open at night during winter	33	38	30	32	31	49
b. ---- Room door usually shut	15	16	12	16	14	19
c. ---- Room door usually not shut	18	22	18	14	16	28
d. Windows almost never open	66	61	69	66	68	50

Source: Newman and Day (1975)

occupied, and the number of open windows and climatic variables were recorded. At this site (where wind was the predominant driving force for infiltration) the following regression model for total air change rates was derived:

$$INF = A + BW + C\ (n + 1.4m) + D\ (n + 1.4m)\ W$$

where INF is total air-changes per hour; W is wind speed in mph; A, B, C, and D are constants; n is the number of small windows open (top hung vent-lights"): and m is the number of casement windows open. The fit of the regression model for two sets of data (which represent the range of common window opening behavior) is shown in Figure 5-1. To date, this is the only model incorporating window opening behavior on the total air change rate of a building.

In addressing the issue of occupant motivation for opening windows, it was found that external weekly mean temperature accounted for over 70 percent of the variance in the number of open windows. A further 10 percent of the variance could be attributed to wind speed. This can be seen in Figure 5-2. As external temperature decreased, the number of open windows was reduced sharply; and as wind speed increased (at any temperature), the number of open windows was also reduced. Large variances were found to exist in window opening behavior from house to house and with each household from day-to-day. It is of interest that the air tightness of closed but occupied houses in this sample was 1.5 air changes per hour; this is similar to that which Caffey (1979) found to be typical in the United States.

When the above regression model was applied to observed window opening behavior, a clear relationship was found between total air-change rates and external temperature. As Figure 5-3

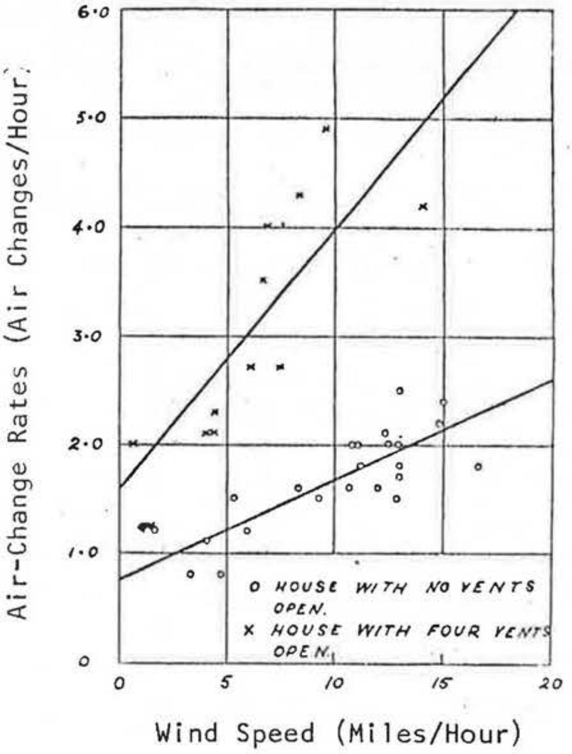
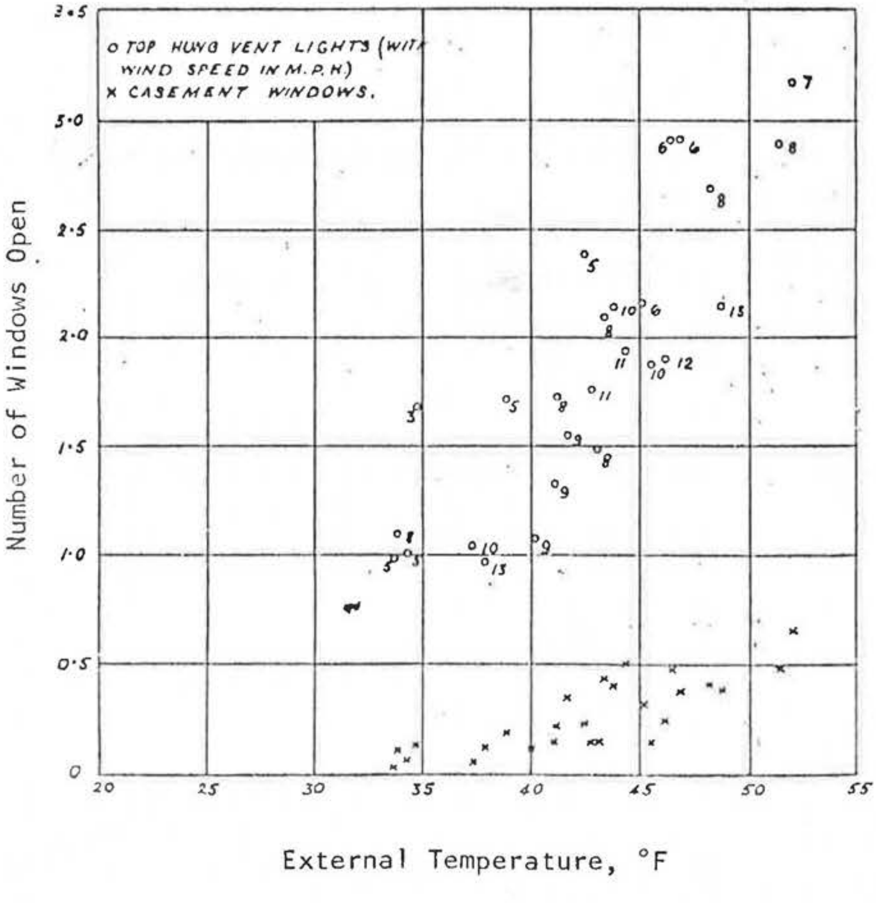


Figure 5-1

Variation of House Air-Change Rate with Wind Speed and Number of Windows Open

Figure 5-2

Effect of External Temperature On Site Window Opening



Source: Dick and Thomas (1951)

Figure 5-3

Effect of External Temperature on
Total Air-Change Rates of Occupied Houses

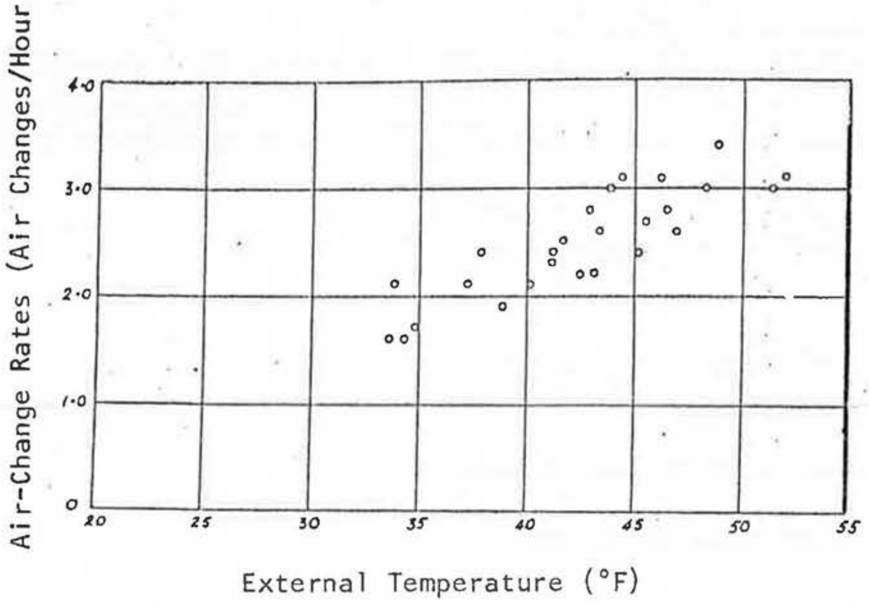
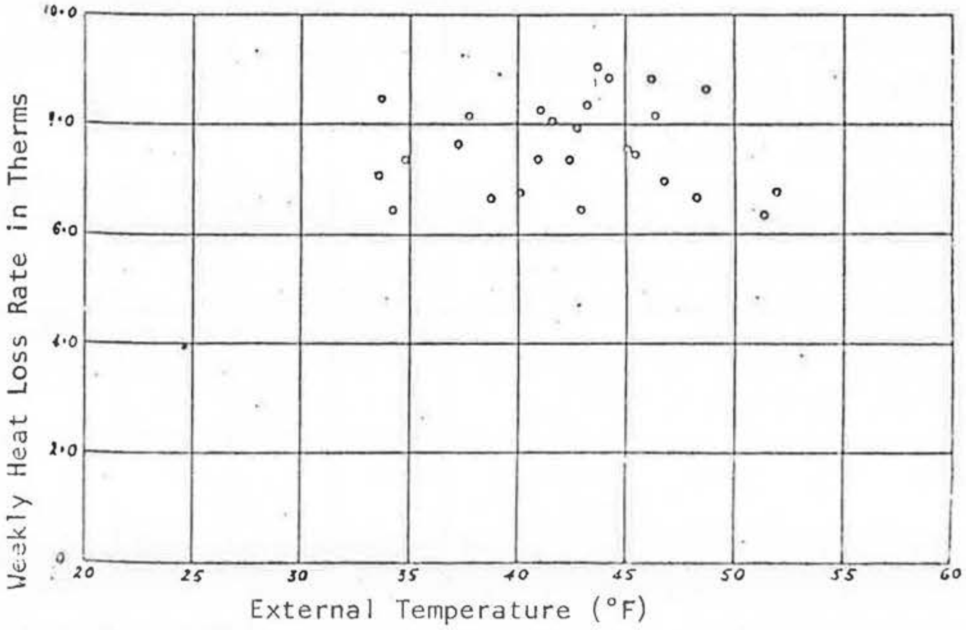


Figure 5-4

Effect of External Temperature on Rate of Heat Loss
Due to Total Air-Changes of Occupied Houses



Source: Dick and Thomas (1951)

shows, as external temperatures increase, so does the total air change rates

Weekly heat loss rates due to total air changes were computed for different weekly temperatures by using the following equation:

$$Z = 0.21\Delta T\ (INF)$$

where Z is the heat loss rate in therms per week due to total air changes; ΔT is the difference between weighted house temperature and external temperature in °F and INF is the equivalent air-change rate in air changes per hour. The results of this computation are shown in Figure 5-4. Dick and Thomas pointed out that as external temperature decreased by 1°F, ΔT was only increased by .5°F in the average home. This was due to economic considerations, window opening behavior, and in some cases the maximum output of home heating systems. Because of this, changes in the terms ΔT and INF largely offset each other and the weekly heat loss rate due to total air-changes was therefore found to be independent of external temperature for these homes.

Brundett (1977) observed window opening behavior in 123 houses at Connahs Quay, England for a period of one year and also recorded climatic conditions. When the number of rooms with open windows was compared to mean monthly temperature, the results were found to be similar to those of Dick and Thomas (1951). Figure 5-5 shows this relationship for Brundrett's sample (comprised of two housing groups) and also includes data from Dick and Thomas (1951) for comparison.

Brundrett points out that in Britain there is a strong link between mean daily temperature and mean daily humidity. Therefore, in this climate, window opening behavior could be motivated by external temperature or external humidity. Figure 5-6 shows the

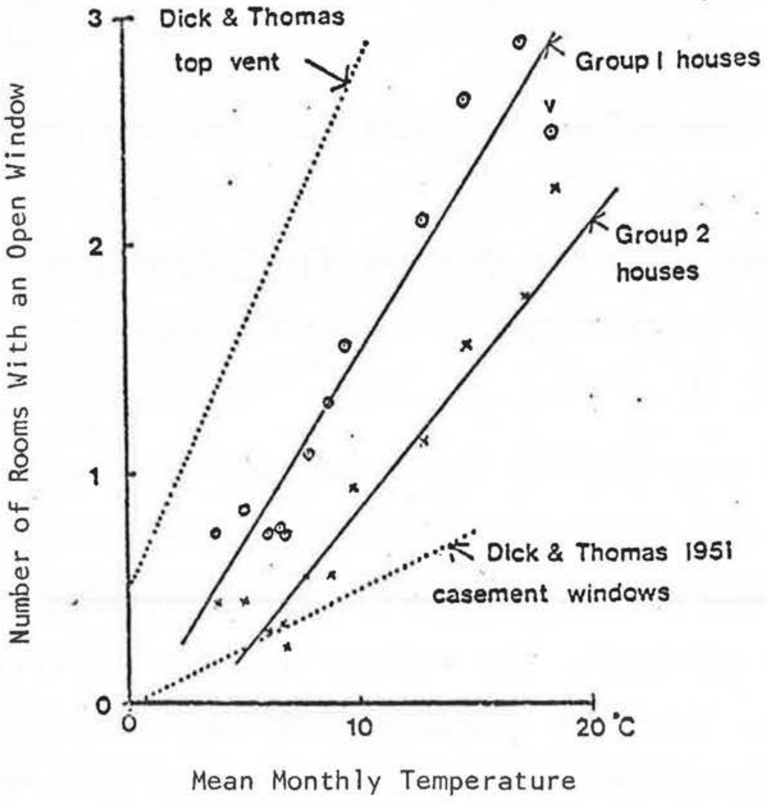


Figure 5-5

Relationship Between Open Windows and External Temperature

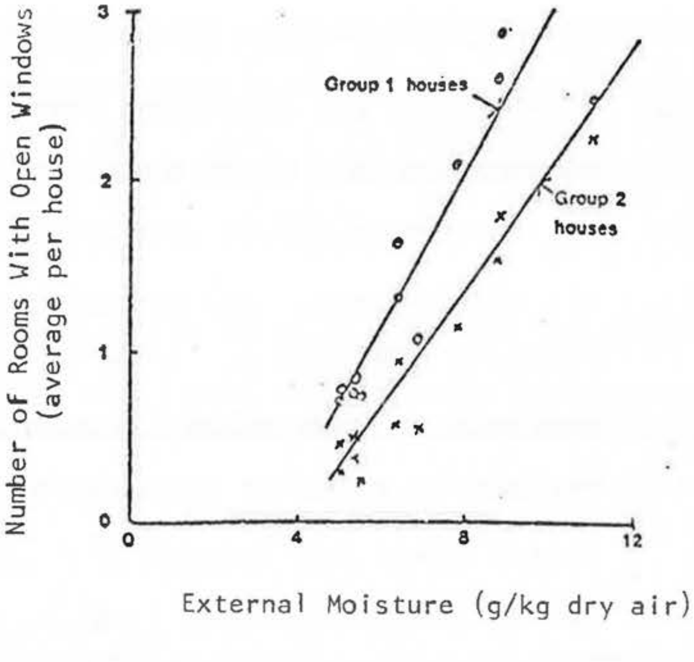


Figure 5-6

Relationship Between Open Windows and Moisture Content of External Air

Source: Brundrett (1977)

e number of rooms having open windows with
ontent of external air. It is worth noting that
and Thomas (1951) did not find any significant relationship
between these two variables. It appears that the combined effects
of outdoor temperature and outdoor humidity on occupants' use of
ventilation requires further research under different climatic
conditions and with houses that have different heating systems
(such as central forced air as opposed to radiant heating systems).

LBL (1978) cites correspondence with Adamson (Sweden) in which
suggests that future studies be conducted to determine the
endence of ventilation (both by natural and mechanical means) on
or temperature, indoor relative humidity, indoor activities
as cooking or smoking), and outdoor temperature. LBL proposes
rther inclusion of constraining factors such as outside ambient
evels, outside ambient pollution levels, and precipitation.
ther understanding of a households' motivations for using
on can be gained from surveying occupants. For example,
975) surveyed households to determine lifestyle patterns
uring the air-change rates of occupied homes. The
ded questions pertaining to occupation patterns and
. Brundrett (1977) found from his survey that the
hold members at home during the day and the total
the major demographic determinants of the number
windows.

nts out that predictive models for total air-
t accounted for either occupant window opening
air requirements. LBL (1978) suggests that

a data base be developed so that the probability of the number of open windows can be predicted as function of time of day. Further, while the development of models for multiple window openings is thought to be a long way off, this proposed data base could be used to develop "average" numbers of open windows for different weather conditions. In sum, an acceptable model for air-change rates need to account for "average occupant behavior."

Mechanical Ventilation Effects

Occupant use of mechanical ventilation and its impact on total air change rates in buildings has been little studied to date, but should be considered a significant research area.

Caffey (1979) measured air leakage rates in 50 homes and found mechanical ventilation components to contribute the following percentages to the total air change rate: kitchen stove vent--5 percent; clothes dryer exhaust vent--3 percent; and bathroom vent--1 percent. Jordan, Erickson, and Leonard (1963) also found significant increases in total air change rates when the above three ventilation fans were operated simultaneously (LBL 1978). It is difficult to quantify the effects of occupant behavior here because as Caffey (1979) has found, many ventilators have a "butterfly damper" that opens due to slight pressure differences rather than solely when ventilator fans are operating.

Heating System Operation and Occupant Effects

LBL (1978) points out that after window and door opening behavior, the operation of the heating system is the next most important area which occupants influence the air change rate of a building. By adjusting their thermostats (thereby changing the difference between indoor and outdoor temperatures) occupants alter the stack pressure which changes infiltration rates of a building. Where fossil fuel heating systems are present, occupant temperature control also affects the heat losses up the flue and the intake of air for combustion and dilution of noxious gases. Therefore, occupant temperature control can have a large (though unintentional) effect of the infiltration rate of a building.

Conclusion

In sum, occupants have a large effect on the total air change rate of a building. A variety of indoor and outdoor factors combine to determine occupant use of ventilation. Besides direct effects from natural and mechanical ventilation, occupants have an indirect effect on infiltration rates through their operation of the heating system.

As IEA (1979) states, more research is needed to compare air change rates in closed unoccupied buildings to air change rates when occupied. Such research should be conducted in a variety of climates. With more data of this type available, the effects of climate, indoor conditions and occupant behavior can be more fully understood.

6.0 INDOOR AIR QUALITY AND INFILTRATION

In recent years, as structures are being built tighter, people have become concerned about the quality of the indoor environment. As Hollowell (1978) states, "Chemical and biological contaminants released into indoor environments are undesirable but often unavoidable by-products of human activity and from the use of building materials and furnishings within closed spaces." However, outdoor pollutants are swept into the house via infiltration. The rate at which pollutants are generated and the level of infiltration are the two major factors in determining the indoor air quality.

As Roseme (1979) points out, "ventilation is required for the following reasons:

- to establish a satsifactory balance between the metabolic gases (oxygen and carbon dioxide) in the occupied environment;
- to remove excess heat and moisture arising from internal sources;
- to dilute human and non-human odors to a level below an acceptable olfactory threshold;
- to remove contaminants produced by activities, furnishings, construction materials, etc., in the occupied spaces."

Thus it is apparent that the indoor air quality is affected by many factors and that the level of poisonous gases and particulate pollution can have adverse health effects. Furthermore, the humidity level is a significant factor affecting the integrity of building components and furnishings and can affect the growth of mold and fungi.

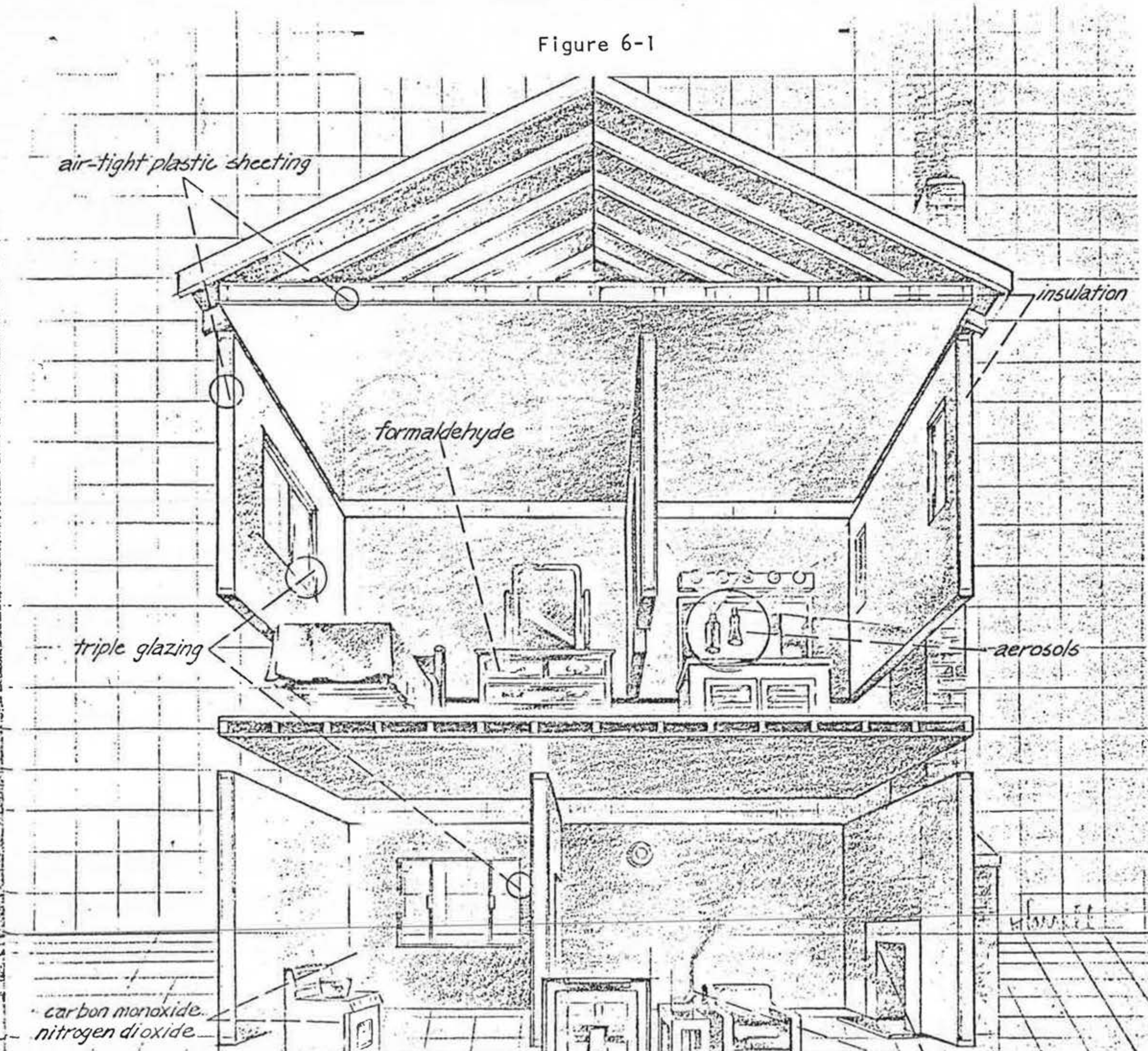
The health effects resulting from contaminants in the air can range from minor irritation of the eyes, nose, and throat to severe respiratory difficulties due to high levels of smoke and toxic vapors. Furthermore, depending on the sensitivity of the occupant, their allergies could be exacerbated by the presence of particulate matter, microorganisms (caused by high humidity levels), and vapors. If the air becomes stale then annoying odors, dust, and smoke will accumulate making the problem worse. One of the most severe health effects is the increased risk of circulatory difficulties due to carbon monoxide and tobacco smoke.

The first section of this chapter will discuss some of the major pollutants existing in the indoor air environment. The second section will present a few ventilation techniques which can be used to control the quality of indoor air. However, the current state-of-the-art for evaluating indoor air quality lacks detailed clinical data on health effects and large-scale field measurements which would determine the magnitude of this problem.

6.1 Typical Indoor Air Pollutants

The indoor environment is a complex mixture of pollution sources and sinks. Typical combustion processes (e.g., cooking, smoking, and heating) generate gaseous and particulate pollutants. Furthermore, the use of toxic cleaning chemicals, so-called air freshening chemicals, and a wide variety of other chemicals used throughout the house can lead to pollution build-up. Finally, the materials used in the construction of the home may themselves be sources of pollution. Figure 6-1 depicts the various types of pollution sources and shows where they may occur in a typical house. Some of the major indoor and outdoor air pollutants are presented in Table 6-1 along with the sources of these pollutants. As a result of these and other pollutants, Sweden, Denmark, and West Germany have issued indoor air quality standards.

Figure 6-1



Source: Science 80, March/April 1980

Table 6-1

Indoor Air Pollution in Residential Buildings

SOURCES	POLLUTANT TYPES
OUTDOOR	
Ambient Air	SO_2 NO, NO_2, O_3, Hydrocarbons, CO, Particulates
Motor Vehicles	CO, Pb
INDOOR	
Building Construction Materials	
Concrete, stone	Radon
Particleboard	Formaldehyde
Insulation	Formaldehyde, Sulfates
Adhesives	Organics
Paint	Mercury, Organics
Building Contents	
Heating and cooking combustion appliances	CO, SO_2, NO, NO_2, Particulates
Furnishings	Organics, Odors
Water service; natural gas	Radon
Human Occupants	
Metabolic activity	CO_2, NH_3, Organics, Odors
Human Activities	
Tobacco smoke	CO, NO_2, HCN, Organics, Odors
Aerosol spray devices	Fluorocarbons, Vinyl Chloride
Cleaning and cooking products	Hydrocarbons, Odors, NH_3
Hobbies and crafts	Organics

Source: Hollowell (1978).

Four pollutants receiving considerable attention at this time are nitrogen dioxide (NO_2), carbon monoxide (CO), formaldehyde (HCHO), and radon gas (Rn-222). A recent study conducted by the Harvard School of Public Health (between May 1977 and April 1978), measured the levels of indoor and outdoor air pollutants in 80 homes located in 6 cities. These measurements indicated that NO_2 levels exceed the outdoor level for all homes. The levels for homes using gas cooking stoves exceeded the levels in homes using electricity for cooking. Furthermore, they found that the level of respirable smoke and dust particles averaged about twice the outside level and that in two of the homes with pack-a-day smokers, the level of particulate pollution exceeded the EPA's health standard.

The levels of NO_2 and CO resulting from the operation of typical residential gas stoves were recently measured in laboratory tests conducted by LBL (Hollowell 1978). They found that when only one top burner was on for approximately 30 minutes the level of NO_2 approached 1.0 mg/m^3 (0.5 ppm) while the operation of the oven for 20 minutes caused the level to increase to 1.5 mg/m^3 (0.8 ppm). These values can be compared to the U.S. short-term NO_2 ambient standard recommending that levels not exceed 0.4 mg/m^3 (0.25ppm) for a period of one hour. Table 6-2 summarizes the short-term NO_2 air standards for several countries. Further tests by LBL indicated that a gas fueled hot air heating system caused the NO_2 level to remain constant at about 1.14 mg/m^3 (0.6 ppm) for 8 hours. LBL's laboratory results of CO and NO_2 levels are presented in Figures 6-2 and 6-3 respectively. The pollution levels are plotted for four different air change rates. Note that the CO level exceeds the one hour air quality standard only when the air change rate approaches 0.24 per hour (this represents

Table 6-2

Recommended and Promulgated Short-Term NO_2 Air Quality Standards

Country	Short-term NO_2 air quality standard ($0.1 \text{ ppm} \approx 190\ \mu g/m^3$)	Status
Canada	0.2 ppm/1 hr	promulgated
(Ontario)	0.1 ppm/24 hr	promulgated
Japan	0.04-0.06 ppm/24 hr	promulgated
U.S.A.	0.25-0.50 ppm/hr	recommended
West Germany	0.15 ppm/short-term exposure	promulgated
WHO/UNEP	0.10-0.17 ppm/hr	recommended

Source: Hollowell (1978)

a relatively tight house). However, if the ventilation rate is less than 2.5 air-changes per hour, then the level of NO_2 resulting from the operation of the oven for one hour at 180°C (350°F) will exceed the one hour air quality standard. Furthermore, using the ventilation rate recommended by ASHRAE (1973) for kitchens (50 cfm) would result in a NO_2 level of 0.76 mg/m^3 (0.4ppm), double the level recommended by the standard. As a result of this research Hollowell concludes that:

> the field and laboratory measurements carried out thus far certainly indicate a potential impact of combustion-generated indoor air pollution on human health; and if borne out by further work, they may ultimately have a large impact on energy conservation strategies for buildings and on the need for more stringent control of air pollution from indoor combustion sources.

Formaldehyde levels have been monitored in a number of residences in the U.S. and Europe. There is evidence that formaldehyde gas escapes from various building materials as a result of diffusion of the gas to the surface. Formaldehyde is used as a binding agent in a number of resins (urea, phenolic, melamine, and acetal) which are in turn used in the production of particle board, plywood, insulation, and textile products. In the production of these materials an excess of formaldehyde is intentionally added to the chemical mixture to insure complete bonding. However, the portion of the formaldehyde that is not chemically bound is free to diffuse through the product and can eventually outgas. A second release mechanism (hydrolysis) results in the liberation of formaldehyde as a result of the chemical combination of water and resin. Thus, for products like particle board and plywood, Hollowell (1978) points out, "The emission rate varies as a function of several parameters, such as the original manufacturing process, quality control of fabrication, porosity, humidity, cutting of the board for final use, etc., as well as the rate of infiltration and ventilation."

Andersen (1975) measured the levels of formaldehyde in 23 Swedish homes. He found that the level of formaldehyde could be correlated with the age of the home but not with weather/climate conditions. He developed a predictive equation that models the level of formaldehyde as a function of exposed board area, room volume, temperature, and humidity levels. His field test and data analysis indicated that in residential structures the half-life of formaldehyde was approximately two years.

Further research has been performed in this country principally on mobile homes. For instance, the states of Wisconsin, Washington, Minnesota, and Oregon have sampled several hundred homes to measure formaldehyde. The vast majority of these homes were sampled as a result of occupant complaints about irritation of the eyes, nose, and throat of various family members. In general, the average level measured was about 0.7 mg/m^3 (0.6 ppm) but the range is from less than 0.12 mg/m^3 (0.1 ppm) to greater than 6 mg/m^3 (5 ppm). A recent study conducted in Wisconsin sampled 65 randomly selected mobile homes. The average formaldehyde concentration measured was about 0.24 mg/m^3 (0.2 ppm), somewhat less than the homes where occupants have complained of irritating symptoms. However, the average age of the mobile homes in the random sample was significantly greater than the average age of the complaint homes. Indeed, the level of formaldehyde in the random sample for homes less than 2.5 years of age was 0.64 mg/m^3 (0.53 ppm) as compared to 0.85 mg/m^3 (0.71 ppm) for the complaint homes less than 2 years old.

As a result of these and other studies several countries have recommended indoor formaldehyde standards. The proposed, recommended, and promulgated formaldehyde standards for ambient, work place, and residential situations are summarized in Table 6-3. The lowest recommended level is 0.12 mg/m^3 (0.1 ppm), significantly less than the concentrations reported above.

Table 6-3

Ambient, Occupational and Indoor Formaldehyde Standards

Country	Ambient Air Standards			Occupational Standards			Indoor Standards		
	Proposed	Recommended	Promulgated	Proposed	Recommended	Promulgated	Proposed	Recommended	Promulgated
United States		0.1 ppm 0.12 mg/m^3			10 ppm < 30 minutes 5 ppm 8 hour ceiling 3 ppm 8 hour TWA 1 ppm-1.2 mg/m^3 30 minutes sampling period 0.1 ppm 90 to 1000 days 0.2 ppm-continuous 0.8-alert 5.0 ppm-abort Space Flight	3 ppm TWA 2 ppm-3 mg/m^3 0.5 ppm - 90 days 1.0 ppm 24 hour 3.0 ppm 1 hour emergency Nuclear Submarine			
Wisconsin, U.S.A.							.4 ppm- (.48 mg/m^3)* .2 ppm- (.24 mg/m^3)**		
Australia					2 ppm-3 mg/m^3 ceiling				
Belgium					2 ppm-3 mg/m^3 ceiling				
Bulgaria						1.0 mg/m^3 MPC			
Czechoslovakia						2 mg/m^3 average 5 mg/m^3 MAC			
Finland						2 ppm-3 mg/m^3 ceiling			
German Democratic Republic						2 mg/m^3 MAK-D 2 mg/m^3 MAK-K			
Federal Republic of Germany			0.03 mg/m^3 MIK		1 ppm 1.2 mg/m^3			0.1 ppm MAC	
Hungary						1 mg/m^3 TWA			
Italy					1.5 mg/m^3 TWA				
Japan					2 ppm-2.5 mg/m^3 TWA				
Netherlands					2 ppm-3 mg/m^3 TLV				0.1 ppm MAC
Poland						2 mg/m^3 ceiling			
Romania					4 mg/m^3 (undetermined)				
Sweden					2 ppm 3 mg/m^3 ceiling			below 0.4 acceptable 0.4 < 0.7 acceptable without irritation > 0.7 unacceptable < 0.1 maximum for new building	
Switzerland						1 ppm-1.2 mg/m^3 MAC			
USSR		Undertermined 0.01 mg/m^3 -0.035 mg/m^3				0.5 mg/m^3 MAC			
Holland								0.12 mg/m^3 MAC	
Denmark						1.0 ppm TLV		0.12 ppm MAC	

Note: TWA = time weighted average
MPC = maximum permissible concentration
MAC = maximum allowable concentration

TLV = threshold limit value
MAK-D = maximum average concentration, 8 hour 45 min. work period
MAK-K = maximum concentration not to exceed 30 minutes
MIK – German outdoor air standard

* Strictly for mobile homes
** After May 1, 1981

Current research has revealed that the levels of formaldehyde can be reduced by various abatement techniques such as sealants, absorbers, and air filters. Studies of effectiveness of these and other techniques are being pursued actively at this time.

The final potentially hazardous indoor pollutant discussed in the literature is radon gas (Rn-222). Radon is the product of radioactive decay of radium-226 which is part of the uranium-238 decay chain. The decay chain starting with radium-226 is presented in Table 6-4. Radium-226 is found as a trace element in most rock and soil. Thus the decay of radium leads to the formation of radon gas which can easily migrate to the surface through the interstitial spaces and be released into the air.

Radon itself is inert; however, the decay of radon (half-life equal to 3.8 days), leads to the production of four short-lived daughter products which are not inert. Most of the radioactive daughter products will become chemically or physically attached to airborne particulates. If these radioactive particulates are inhaled and retained in the lung bronchii, subsequent alpha decay of polonium-218 and polonium-214 will lead to a radiation dose to lungs.

As Budnitz (1978) states, "The concentration of radon in the indoor air depends on the emanating rate from the parent material and on the mechanism for removal, including ventilation." Recent studies have monitored the levels of radon in various residential buildings in the U.S. and Europe. The radioactive levels for five locations are as follows:

San Francisco	0.01 - 0.15	nCi/m^3
Colorado	0.34 - 0.80	nCi/m^3
Chicago	0.10 - 1.40	nCi/m^3
New York City	0.70 - 3.00	nCi/m^3
Sweden	1.0 - 12.00	nCi/m^3

Table 6-4

SELECTED ELEMENTS IN URANIUM DECAY CHAIN*

NUCLIDE	HALF-LIFE(TIME)	MeV (abundance) ALPHA ENERGY	MeV (abundance) BETA ENERGY	MeV (abundance) GAMMA ENERGY
$^{226}_{88}$Ra	1622 years	4.60 (6%), 4.78 (95%)		0.186 (4%)
$^{222}_{86}$Em(Rn)	3.825 days	5.486 (100%)		0.51 (0.07%)
$^{218}_{84}$Po(RaA)	3.05 minutes	5.998 (100%)	0.33 (0.022%)	0.186 (0.03%)
$^{218}_{85}$At(RaA')	2 seconds	6.65 (5%), 6.70 (94%)	unknown (0.1%)	
$^{218}_{86}$Em(RaA'')	0.019 seconds	7.127		
$^{214}_{82}$Pb(RaB)	26.8 minutes		0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{214}_{83}$Bi(RaC)	19.7 minutes	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
$^{214}_{81}$Po(RaC')	1.64×10^{-4} seconds	7.68 (100%)		0.799 (0.014%)
$^{210}_{81}$Tl((RaC'')	1.32 minutes		1.2 (25% 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.310 (21%)
$^{210}_{82}$Pb(RaD)	19.3 years	3.72 (0.000002%)	0.017 (85%) 0.061 (15%)	0.0467 (0.045%)
$^{210}_{83}$Bi(RaE)	5.00 days	4.65 (0.00007%) 4.69 (0.00005%)	1.17 (100%)	
$^{210}_{84}$Po(RaF)	138.4 days	5.298 (100%)		0.802 (0.000012%)
$^{206}_{81}$Tl(RaE'')	4.19 minutes		1.57 (100%)	
$^{206}_{32}$Pb(RaG)	Stable			

Radioactive decay of radium (Ra 226) results in the daughter products in descending order as shown in Table 1. Most of the energy of the radioactivity is as alpha particles.

*Radiological Health Handbook, U.S. Department of Health, Education and Welfare, January 1970, p. 112.

Source: Kusuda (n.d.).

As can be seen from these results, the range of radioactivity varies greatly even at the same geographical location. The values measured in Sweden are substantially higher than U.S. values since Swedish houses are in general much tighter than those existing in the United States.

The impact or dose response characteristics of radon at these low radiation levels on the occupant is not well understood at this time. Thus, it is not known whether radon gas poses a health hazard at these levels. Budnitz (1978) and Hollowell (1978) both recommend that a linear hypothesis type model be used to assess the potential dangers until the situation is better understood.

Regardless of the indoor air pollutant it is possible to derive rate equations which track the concentrations as a function of time. Kusuda (1976) rate equation takes the following form:

$$V \frac{dc}{dt} = 100\ NG + \dot{V}\ (C_o - C)$$

where

V = the volume of structure

C = concentration of contaminants in percent

N = number of occupants

$\dot{V}$ = volumetric flow rate of air

G = rate of generation of the pollutant

C_o = concentration of outside contaminant in percent

The solution of this equation is as follows:

$$C - C_1 = (C_o + M - C_1)\ (1 - e^{-(\dot{V}/V)\ t})$$

where

C_1 = the initial concentration(in percent) at $t = 0$

M = $100\ NG/\dot{V} = 100\ G/(\dot{V}/V)$

Note that the quantity ($\dot{V}/V$) is the number of air-changes per unit time and is usually the value expressed by ventilation standards. The ventilation values recommended for residential structures is presented in Table 6-5. The quantity ($1 - e^{-(\dot{V}/V)t}$) is a measure of how quickly steady state or equilibrium is obtained. The value of this function is presented in Figure 2-2. Thus if $\dot{V}/V \geq 4$ (~8 hours) the steady state solution becomes:

$$C_\infty = C_o + M$$

Since M is a well defined function, then the ultimate concentration is just the initial value plus a constant source term.

In a second report by Kusuda (n.d.), he develops the rate equation for a radioactive substnace like radon. The rate equation takes the following form:

$$\frac{dn}{dt} = \frac{\dot{V}}{V}(N - N_o) - \lambda N + S$$

where

N = radioactive element concentration (atoms/liter)

N_o = outside level of this element (atoms/liter)

$\dot{V}$ = volumetric air flow rate

V = volume of structure

λ = decay constant (1.258×10^{-4}/min. = 0.0075/hr.)

S = total radon daughter source strength (atoms/liter)

t = time (hr.)

The solution of this equation is as follows:

$$N = N_i + \left[\frac{S + (\dot{V}/V)N_o}{\dot{V}/V + \lambda}\right]\left[1 - e^{-(\dot{V}/V + \lambda)t}\right]$$

Table 6-5

ASHRAE Ventilation Requirements

Building Classifications	Ventilation Requirements (cubic feet per minute per human occupant)	
	Minimum	Recommended
Single Family Residential		
General Living Areas, Bedrooms	5	7-10
Kitchens	20	30-50
Baths, Toilet Rooms	20	30-50
Basements, Utility Rooms	5	5
Multiple Family Residential		
General Living Areas, Bedrooms	5	7-10
Kitchens	20	30-50
Baths, Toilet Rooms	20	30-50
Basements, Utility Rooms	5	7-10
Mobile Homes	5	7-10

Source: Hollowell (1978).

where

N_i = the initial level of the radioactive element (atoms/liter)

If we define A as the radioactive level (nCi/m^3) it would equal λN. Rearranging the above equation and substituting the quantity A we obtain:

$$A = A_i + \left(\frac{S\lambda}{INF} + A_o \right) \left[1 - e^{-(INF + \lambda)t} \right]$$

where

INF = the number of air changes per hour

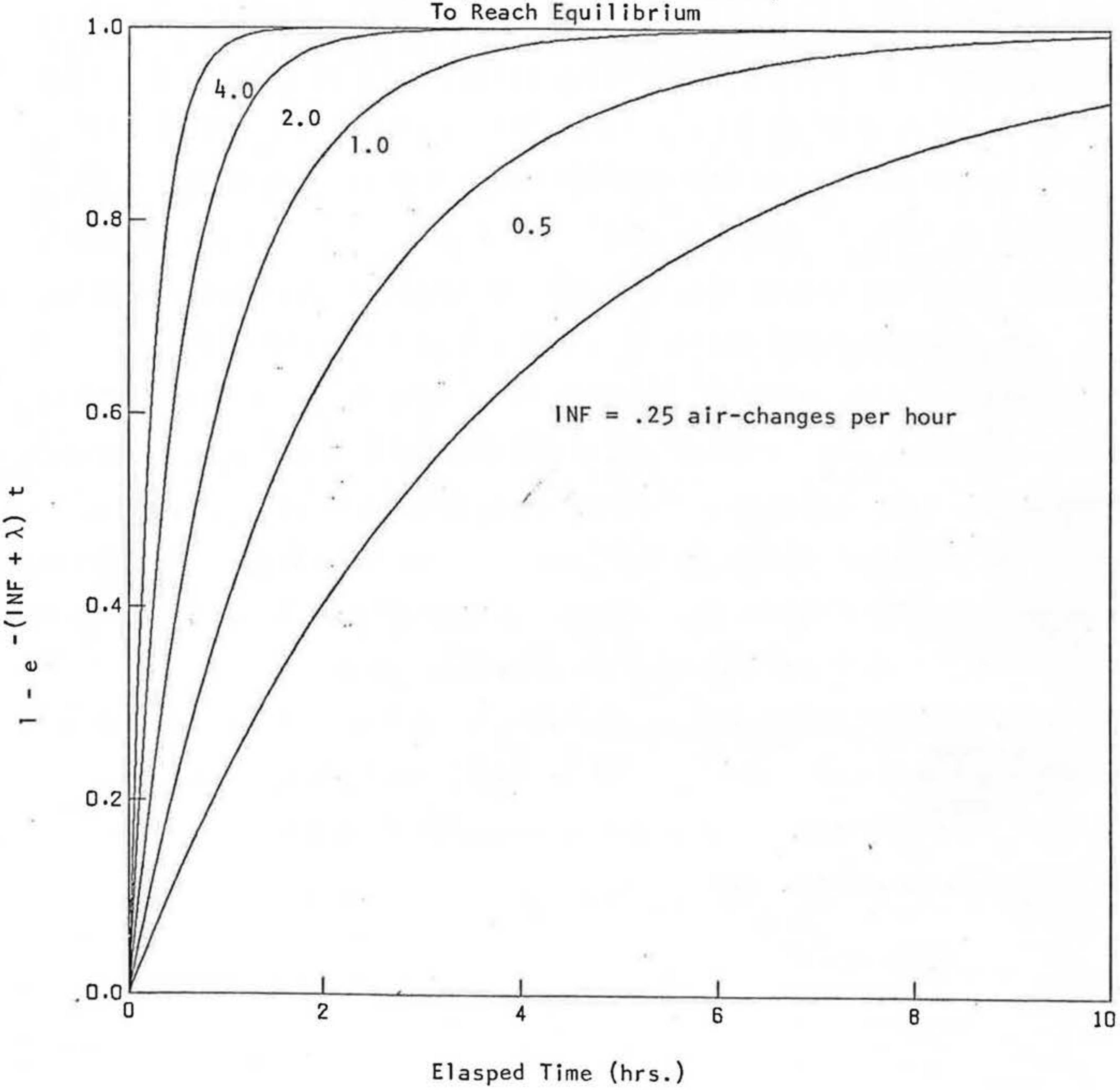
Thus, the rate at which equilibrium is reached is expressed by the exponential term. The value of $\left[1 - e^{-(INF + \lambda)t} \right]$ has been plotted in Figure 6-4. For typical levels of infiltration equilibrium will be obtained on the order of hours. However, as the houses become tighter this equalization period could approach 15-20 hours. In any case, once equilibrium is reached it is apparent that the level of radioactivity is inversely proportional to the level of infiltration.

6.2 Controlled Ventilation

Fresh air is required so that a safe and healthy living environment can be sustained. In the past the high levels of infiltration have ensured the adequacy of the indoor environment but now tighter homes have focused attention on indoor pollution and moisture problems. There are several methods for maintaining a habitable environment; however, the principal mechanism to control the movement of air is through ventilation.

Figure 6-4

Time Required for Radioactivity To Reach Equilibrium



Mechanical ventilation can take several forms. For instance, air-to-air heat exchangers are being used in residential construction today. These systems are manufactured principally in Europe, Japan, and Canada. The cost of these units ranges from $300 to $2500. The systems usually consist of two fans; one to remove the indoor air and the other to draw in the outside air. The two air streams are separated by various membrain materials (e.g. paper, metal, plastic, etc.) so that the inside air does not contaminate the fresh outside air. The principle objective of these systems is to preheat or cool the incoming air as much as possible (i.e. the transfer of sensible heat). However, the transfer of latent energy is difficult to obtain technically. For instance, the use of a water permeable membrane allows the transfer of the latent heat, but it also allows the transfer of water soluable pollutants. Thus, the out-going air will potentially pollute the fresh incoming air. To alleviate this problem, air purification through the use of filters, electrostatic precipitators, air washers, and gas absorbers may be required. Researchers at LBL have recently begun a program to evaluate several residential air-to-air heat exchangers.

APPENDIX A

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APPENDIX B

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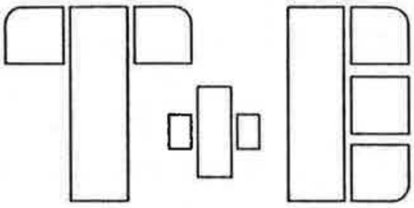

Note: Several of the listings presented in the LBL bibliography are also listed in Appendix A. Therefore the listings appearing in both appendices are denoted by bullets "●".

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 AUTHOR = Arens, E. A.;
 AUTHOR = Williams, P. B.;
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● TITLE = Measurement of Infiltration in Two Residences;
 AUTHOR = Bahnfleth, D. R.;
 AUTHOR = Moseley, T. D.;
 AUTHOR = Harris, W. S.;
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 AUTHOR = Barrett, R. E.;
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    AUTHOR = Beyea, J.;
    AUTHOR = Harrje, D. T.;
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    TYPE = CONF. PROC.;
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●   TITLE = A Model Correlating Air Tightness and Air Infiltration in
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   REPORT.NO = 1916;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Residential Energy Conservation:  The Case for House
Doctors;
 AUTHOR = Dutt, G. S.;
 TYPE = CONF. PROC.;
   DATE = 07/31/79;
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 TITLE = Forced Ventilation for Cooling Attics in Summer;
 AUTHOR = Dutt, G. S.;
 AUTHOR = Harrje, D. T.;
 TYPE = REPORT;
   DATE = 1978;
   PUBLISHER.NAME = Center for Environmental Studies;
   PUBLISHER.CITY = Princeton Univ.;

 TITLE = The Effect of Material Porosity on Air Infiltration;
 AUTHOR = Dutt, G. S.;
 TYPE = REPORT;
   DATE = 02/04/77;
   REPORT.NO = Twin Rivers Project: Dutt note #3;
   PUBLISHER.NAME = Princeton Univ.;

 TITLE = Condensation in Attics: Are Vapor Barriers Really the
Answer?;
 AUTHOR = Dutt, G. S.;
 TYPE = REPORT;
   DATE = 05/--/79;
   PUBLISHER.NAME = Center for Energy and Environmental Studies;
   PUBLISHER.CITY = Princeton, NJ 08544;

 TITLE = Natural Ventilation of Modern Tightly Constructed Homes;
 AUTHOR = Elkins, R. H.;
 AUTHOR = Wensman, C. E.;
 TYPE = REPORT;
   DATE = 02/--/71;
   VOLUME.TITLE = AGA Conference on Natural Gas Research and
Technology;
   VOLUME.NO = 28;

 TITLE = The Neutral Zone in Ventilation;
 AUTHOR = Emswiler, J. E.;
 TYPE = REPORT;
   DATE = 01/--/26;
   VOLUME.TITLE = ASHVE Trans.;
   VOLUME.NO = 32;
   PAGES = 59-74;
   REPORT.NO = 738;
   PUBLISHER.NAME = ASHVE;

 TITLE = Air Infiltration Measurements on the NBS Experimental
Building;
 AUTHOR = Faison, T. K.;
 TYPE = REPORT;
   VOLUME.TITLE = Building Science Series;
   VOLUME.NO = 45;
   PAGES = 28-;

 TITLE = Ridge Vent Effects on Model Ventilation Characteristics;
 AUTHOR = Froehlich, D. P.;
 AUTHOR = Hellickson, M. A.;
 AUTHOR = Young, H. G.;
 TYPE = REPORT;
   DATE = 04/--/75;
   VOLUME.TITLE = ASAE Trans.;
   VOLUME.NO = 18;
   PAGES = 690-693;
   REPORT.NO = 74-4055;
   PUBLISHER.NAME = ASAE;
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 TITLE = Air Infiltration Effects on the Thermal Transmittance of
Concrete Building Systems;
 AUTHOR = Funkhouser, J. R.;
 TYPE = REPORT;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 85 part 1;
   REPORT.NO = PH-79-11;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Measurement of Ventilation Rates with Radioactive Tracers;
 AUTHOR = Gerrard, M.;
 TYPE = JOURNAL;
   DATE = 09/--/68;
   VOLUME.TITLE = ASHRAE J.;
   VOLUME.NO = 10;
   PAGES = 47-50;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Summertime Infiltration Rates in Mobile Homes;
 AUTHOR = Goldschmidt, V. W.;
 AUTHOR = Wilhelm, D. R.;
 TYPE = REPORT;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 85 part 1;
   PAGES = 840-850;
   REPORT.NO = PH-79-10;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, NY;

 TITLE = Wintertime Infiltration Rates in Mobile Homes;
 AUTHOR = Goldschmidt, V. W.;
 AUTHOR = Leonard, R. G.;
 AUTHOR = Ball, J. E.;
 AUTHOR = Wilhelm, D. R.;
 TYPE = DRAFT;
   DATE = 1978;
   VOLUME.TITLE = to be published in ASTM STP, 1978 or 1979;

 TITLE = Infrasonic Impedance Measurements of Buildings for Air
Leakage Determination;
 AUTHOR = Graham, R. W.;
 TYPE = THESIS;
   DATE = 05/--/77;
   PUBLISHER.NAME = Syracuse Univ.;

 TITLE = An Intercomparison of Tracer Gases Used for Air
Infiltration Measurements;
 AUTHOR = Grimsrud, D. T.;
 AUTHOR = Sherman, M. H.;
 AUTHOR = Janssen, J. E.;
 AUTHOR = Pearman, A. N.;
 AUTHOR = Harrje, D. T.;
 TYPE = REPORT;
   DATE = 11/--/79;
   VOLUME.TITLE = LBL Report No.9394;
   PAGES = 1-13;
   REPORT.NO = LBL 9394;
   PUBLISHER.NAME = Technical Information Department, LBL;
   PUBLISHER.CITY = Berkeley, CA 94720;
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 TITLE = Case Studies in Air Infiltration;
 AUTHOR = Grimsrud, D. T.;
 TYPE = REPORT;
   DATE = 05/--/78;
   VOLUME.TITLE = LBL Report - 7830;
   REPORT.NO = LBL-7830;
   PUBLISHER.NAME = Technical Information Department, LBL;
   PUBLISHER.CITY = Berkeley, CA;

 TITLE = Air Leakage, Surface Pressures and Infiltration Rates in
Houses;
 AUTHOR = Grimsrud, D. T.;
 AUTHOR = Sherman, M. H.;
 AUTHOR = Diamond, R. C.;
 AUTHOR = Sonderegger, R. C.;
 TYPE = CONF. PROC.;
   DATE = 05/--/79;
   VOLUME.TITLE = CIB Symp. on Energy Cons. in the Built Environment;
   VOLUME.NO = 2;
   PAGES = 111-120;
   PUBLISHER.NAME = Danish Building Research Institute;
   PUBLISHER.CITY = Copenhagen, Denmark;
 TYPE = REPORT;
   DATE = 03/--/79;
   VOLUME.TITLE = LBL Report 8828;
   REPORT.NO = LBL 8828;
   PUBLISHER.NAME = Technical Information Department, LBL;
   PUBLISHER.CITY = Berkeley, CA;

 TITLE = Infiltration and Air Leakage Comparisons:  Conventional
and Energy-Efficient Housing Designs;
 AUTHOR = Grimsrud, D. T.;
 AUTHOR = Sherman, M. H.;
 AUTHOR = Blomsterberg, A. K.;
 AUTHOR = Rosenfeld, A. H.;
 TYPE = CONF. PROC.;
   DATE = 10/--/79;
   VOLUME.TITLE = Changing Energy Use Futures;
   PAGES = 1351-1358;
   PUBLISHER.NAME = Pergamon Press;
   PUBLISHER.CITY = New York, NY;
 TYPE = REPORT;
   DATE = 10/--/79;
   VOLUME.TITLE = LBL Report - 9157;
   REPORT.NO = LBL 9157;
   PUBLISHER.NAME = Technical Information Department, LBL;
   PUBLISHER.CITY = Berkeley, CA;
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●   TITLE = Infiltration -- Pressurization Correlations: Detailed
   Measurements on a California House;
    AUTHOR = Grimsrud, D. T.;
    AUTHOR = Sherman, M. H.;
    AUTHOR = Diamond, R. C.;
    AUTHOR = Condon, P. E.;
    AUTHOR = Rosenfeld, A. H.;
    TYPE = JOURNAL;
      DATE = 1979;
      VOLUME.TITLE = ASHRAE Trans.;
      VOLUME.NO = 85 part 1;
      PAGES = 851-865;
      PUBLISHER.NAME = ASHRAE;
      PUBLISHER.CITY = New York, N.Y.;
    TYPE = REPORT;
      DATE = 12/--/78;
      VOLUME.TITLE = LBL Report - 7824;
      REPORT.NO = LBL-7824;
      PUBLISHER.NAME = Technical Information Department, LBL;
      PUBLISHER.CITY = Berkeley, CA;

    TITLE = Air Leakage Characteristics and Weatherization Techniques
   for Low-Income Housing;
    AUTHOR = Grot, R. A.;
    AUTHOR = Clark, R. E.;
    TYPE = REPORT;
      DATE = 1979;

    TITLE = The Need for Improved Airtightness in Buildings;
    AUTHOR = Handegord, G. O.;
    TYPE = REPORT;
      DATE = 07/25/77;
      PUBLISHER.NAME = conf. on Ventilation versus Energy Conservation
   in Buildngs;
      PUBLISHER.CITY = Henniker, New Hampshire;

    TITLE = Home Ventilation Rates:  A Literature Survey;
    AUTHOR = Handley, T. H.;
    AUTHOR = Barton, C. J.;
    TYPE = REPORT;
      DATE = 09/--/73;
      VOLUME.NO = c;
      REPORT.NO = ORNL-TM-4318;
      PUBLISHER.NAME = Oak Ridge National Labs.;
      PUBLISHER.CITY = Oak Ridge, Tenn.;

●   TITLE = Locating and Eliminating Obscure but Major Energy Losses
   in Residential Housing;
    AUTHOR = Harrje, D. T.;
    AUTHOR = Dutt, G. S.;
    AUTHOR = Beyea, J.;
    TYPE = REPORT;
      DATE = 1979;
      PUBLISHER.NAME = Center for Environmental Studies;
      PUBLISHER.CITY = Princeton, N.J.;
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●    TITLE = Automated Instrumentation for Air Infiltration
    Measurements in Buildings;
     AUTHOR = Harrje, D. T.;
     AUTHOR = Hunt, C. M.;
     AUTHOR = Treado, S. J.;
     AUTHOR = Malik, N. J.;
     TYPE = REPORT;
       DATE = 04/--/75;
       REPORT.NO = 13;
       PUBLISHER.NAME = Center for Environmental Studies;
       PUBLISHER.CITY = Princeton Univ., Princeton, N.J.;

     TITLE = Automated Air Infiltration Measurements and Implications
    for Energy Conservation;
     AUTHOR = Harrje, D. T.;
     AUTHOR = Grot, R. A.;
     TYPE = CONF. PROC.;
       DATE = 10/--/77;
       VOLUME.TITLE = Proc. of the Int. Conf. on Energy Use Management;
       PAGES = 457-464;
       PUBLISHER.NAME = Pergamon;
       PUBLISHER.CITY = New York, N.Y.;

     TITLE = Air Infiltration Reduction through Retrofitting;
     AUTHOR = Harrje, D. T.;
     AUTHOR = Mills, T. A.;
     TYPE = REPORT;
       PUBLISHER.NAME = Center for Environmental Studies, Princeton;
       PUBLISHER.CITY = Princeton, N.J.;

●    TITLE = Dynamic Characteristics of Air Infiltration;
     AUTHOR = Hill, J. E.;
     AUTHOR = Kusuda, T.;
     TYPE = REPORT;
       DATE = 01/26/75;
       VOLUME.TITLE = ASHRAE Trans.;
       VOLUME.NO = 81 part 1;
       PAGES = 168-185;
       REPORT.NO = 2337;
       PUBLISHER.NAME = ASHRAE;
       PUBLISHER.CITY = New York, N.Y.;

●    TITLE = Impace of Reduced Infiltration and Ventilation of Indoor
    Air Quality in Residential Buildings;
     AUTHOR = Hollowell, C. D.;
     AUTHOR = Berk, J. V.;
     AUTHOR = Traynor, G. W.;
     TYPE = REPORT;
       DATE = 1979;
       VOLUME.TITLE = ASHRAE Trans.;
       VOLUME.NO = 85;
       PAGES = 816-827;
       REPORT.NO = PH-79-10;
       PUBLISHER.NAME = ASHRAE ;
       PUBLISHER.CITY = New York, N.Y.;
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 TITLE = Air Leakage Through the Openings in Buildings;
 AUTHOR = Houghten, F. C.;
 AUTHOR = Schrader, C. C.;
 TYPE = REPORT;
   DATE = 01/--/24;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 30;
   PAGES = 105-120;
   REPORT.NO = 686;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Remeasurement of Air Exchange Rates in the Norris Cotton
Federal Office Building after Retrofitting to Reduce Leakage;
 AUTHOR = Hunt, C. M.;
 AUTHOR = Richtmyer, T. E.;
 TYPE = REPORT;
   DATE = 04/--/79;
   PUBLISHER.NAME = National Bureau of Standards;
   PUBLISHER.CITY = Washington, D.C.;

●  TITLE = Air Infiltration Measurements in a Four-Bedroom Townhouse
Using Sulfur Hexafluoride as a Tracer Gas;
 AUTHOR = Hunt, C. M.;
 AUTHOR = Burch, D. M.;
 TYPE = REPORT;
   DATE = 01/--/75;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 81 part 1;
   PAGES = 186-201;
   REPORT.NO = 2338;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

●  TITLE = Air Infiltration:  A Review of Some Existing Measurement
Techniques and Data;
 AUTHOR = Hunt, C. M.;
 TYPE = REPORT;
   DATE = 03/--/78;
   REPORT.NO = ASTM Symposium ;
   PUBLISHER.NAME = ASTM;

●  TITLE = Air Leakage Measurements in Three Apartment Houses in the
Chicago Area;
 AUTHOR = Hunt, C. M.;
 AUTHOR = Porterfield, J. M.;
 AUTHOR = Ondris, P.;
 TYPE = REPORT;
   DATE = 06/--/78;
   REPORT.NO = NBSIR 78-1475;
   PUBLISHER.NAME = National Bureau of Standards;
   PUBLISHER.CITY = Wash. D.C.;
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 TITLE = Ventilation Measurements in the Norris Cotton Federal
Office Building in Manchester, NH;
 AUTHOR = Hunt, C. M.;
 TYPE = REPORT;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 85 part 1;
   PAGES = 828-839;
   REPORT.NO = PH-79-10;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Energy Savings Due to Changes in Design of Ventilation and
Air Flow Systems;
 AUTHOR = Hutchinson, F. W.;
 TYPE = REPORT;
   DATE = 1977;
   VOLUME.TITLE = Energy and Buildings;
   VOLUME.NO = 1;
   PAGES = 69-76;
   PUBLISHER.NAME = Elsevier Sequoia;
   PUBLISHER.CITY = S.A. Lausanne, the Netherlands;

 TITLE = Measurement of Heating System Dynamics for Computation of
Seasonal Efficiency;
 AUTHOR = Janssen, J. E.;
 AUTHOR = Torborg, R. H.;
 AUTHOR = Bonne, U.;
 TYPE = REPORT;
   DATE = 1977;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 83 part 2;
   REPORT.NO = 2460;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Infiltration In Residential Structures;
 AUTHOR = Janssen, J. E.;
 AUTHOR = Glatzel, J. J.;
 AUTHOR = Torborg, R. H.;
 AUTHOR = Bonne, U.;
 TYPE = REPORT;
   DATE = 1977;
   VOLUME.TITLE = Heat Transfer in Energy Conservation, ASME;
   PAGES = 33-39;
   PUBLISHER.NAME = ASME;

 TITLE = Improvement of Seasonal Efficiency of Residential Heating
Systems;
 AUTHOR = Janssen, J. E.;
 AUTHOR = Bonne, U.;
 TYPE = JOURNAL;
   DATE = 07/--/77;
   VOLUME.TITLE = J. Engineering for Power;
   VOLUME.NO = 99 no. 3;
   PAGES = 329-334;
   PUBLISHER.NAME = J. Engineering for Power;
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● TITLE = Ventilation Theory and Practice;
  AUTHOR = Jennings, B. H.;
  AUTHOR = Armstrong, J. A.;
  TYPE = REPORT;
    DATE = 01/24/71;
    VOLUME.TITLE = ASHRAE Trans.;
    VOLUME.NO = 77;
    PAGES = 50-60;
    REPORT.NO = 2170 RP-17;
    PUBLISHER.NAME = ASHRAE;
    PUBLISHER.CITY = New York, N.Y.;

● TITLE = Infiltration Measurements in Two Research Houses;
  AUTHOR = Jordan, R. C.;
  AUTHOR = Erickson, G. A.;
  AUTHOR = Leonard, R. R.;
  TYPE = REPORT;
    DATE = 06/24/63;
    VOLUME.TITLE = ASHRAE Trans.;
    VOLUME.NO = 69;
    PAGES = 344-350;
    REPORT.NO = 1843;
    PUBLISHER.NAME = ASHRAE;
    PUBLISHER.CITY = New York, N.Y.;

  TITLE = Height Variation of Wind Speed and Wind Distributions
 Statistics;
  AUTHOR = Justus, C. G.;
  AUTHOR = Mikhail, A.;
  TYPE = REPORT;
    DATE = 05/--/76;
    VOLUME.TITLE = Geophys. Res. Let.;
    VOLUME.NO = 3 no.5;
    PAGES = 261-264;
    PUBLISHER.NAME = American Geophysical Union;

  TITLE = Improved Treatment of Infiltrative Building Heat Losses
 and Effective Outside Temperatures;
  AUTHOR = Keller, D. V.;
  TYPE = REPORT;

  TITLE = Air Infiltration in Buildings Due to Wind Pressures
 Including some Neighboring Body Effects;
  AUTHOR = Kelnhofer, W. J.;
  TYPE = REPORT;
    DATE = 1977;
    VOLUME.TITLE = Heat TRansfer in Energy Conservation, ASME;
    PAGES = 47-56;
    PUBLISHER.NAME = ASME;
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 TITLE = Determination of Combined Air Exfiltration and Ventilation
Rates in a Nine-Story Office Building;
 AUTHOR = Kelnhofer, W. J.;
 AUTHOR = Hunt, C. M.;
 AUTHOR = Didion, D. A.;
 TYPE = CONF. PROC.;
   DATE = 04/12/76;
   VOLUME.TITLE = Proceedings of Conference on Improving Efficiency
and Performance of HVAC Equipment and Systems for  Commercial and
Industrial Buildings;
   PAGES = 322-329;
   PUBLISHER.NAME = Purdue Univ.;

 TITLE = A Study of Humidity Variations in Canadian Houses;
 AUTHOR = Kent, A. D.;
 AUTHOR = Handegord, G. O.;
 AUTHOR = Robson, D. R.;
 TYPE = REPORT;
   DATE = 06/27/66;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 72 part 2;
   PAGES = II.1.1 - II.1.8;
   REPORT.NO = 1998;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Ventilation Measurements as an Adjunct to Radon
Measurements in Buildings;
 AUTHOR = Knutson, E. O.;
 AUTHOR = Franklin, H.;
 TYPE = REPORT;
   PUBLISHER.NAME = E.R.D.A.;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Programmed Computer Model of Air Infiltration in Small
Residential Buildings with Oil Furnace;
 AUTHOR = Konrad, A.;
 AUTHOR = Larson, B. T.;
 AUTHOR = Shaw, C. Y.;
 TYPE = REPORT;
   DATE = 03/--/78;
   PUBLISHER.NAME = NRCC, Division of Building Research;
   PUBLISHER.CITY = Ottawa, Canada;

 TITLE = Pressure Drop and Flow Characteristics of Short Capillary
Tubes at Low Reynolds Numbers;
 AUTHOR = Kreith, F.;
 AUTHOR = Eisenstadt, R.;
 TYPE = REPORT;
   DATE = 07/--/57;
   VOLUME.TITLE = ASME Trans.;
   VOLUME.NO = 79;
   PAGES = 1070-1078;
   REPORT.NO = 56--SA-15;
   PUBLISHER.NAME = ASME;
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 TITLE = An Automated Air Infiltration Measuring System Using SF-6
Tracer Gas in Constant Concentration and Decay Methods;
 AUTHOR = Kumar, R.;
 AUTHOR = Ireson, A. D.;
 AUTHOR = Orr, H. W.;
 TYPE = REPORT;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 85 part 2;
   REPORT.NO = 2553;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Air Leakage Measurement of Large Building;
 AUTHOR = Kusuda, T.;
 AUTHOR = Hunt, C. M.;
 TYPE = DRAFT;
   DATE = 12/--/77;
   REPORT.NO = Research Proposal to Department of Energy;

 TITLE = Characterization of Building Infiltration by the
Tracer-Dilution Method;
 AUTHOR = Lagus, P. L.;
 TYPE = REPORT;
   DATE = 02/24/77;
   VOLUME.TITLE = Energy;
   VOLUME.NO = 2;
   PAGES = 461-464;
   PUBLISHER.NAME = Pergamon Press;
   PUBLISHER.CITY = Great Britain;

 TITLE = Air Infiltration Through Various Types of Wood Frame
Construction;
 AUTHOR = Larson, G. L.;
 AUTHOR = Nelson, D. W.;
 AUTHOR = Braatz, C.;
 TYPE = JOURNAL;
   DATE = 06/--/30;
   VOLUME.TITLE = J. ASHVE;
   VOLUME.NO = 2;
   PAGES = 509-526;
   PUBLISHER.NAME = ASHVE;

 TITLE = Statistical Analyses of Air Leakage in Split-Level
Residences;
 AUTHOR = Laschober, R. R.;
 AUTHOR = Healy, J. H.;
 TYPE = REPORT;
   DATE = 06/29/64;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 70;
   PAGES = 364-374;
   REPORT.NO = 1900;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;
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 TITLE = Electron Absorption Detectors and Technique for Use in
Quantitative and Qualitative Analysis by Gas Chromatography;
 AUTHOR = Lovelock, J. E.;
 TYPE = REPORT;
   DATE = 04/--/63;
   VOLUME.TITLE = Anal. Chem.;
   VOLUME.NO = 35 no. 4;
   PAGES = 474-481;

 TITLE = Air Infiltration Through Weatherstripped and
Non-Weatherstripped Windows;
 AUTHOR = Lund, C. E.;
 AUTHOR = Peterson, W. T.;
 TYPE = REPORT;
   DATE = 1952;
   REPORT.NO = 35;
   PUBLISHER.NAME = Univ. of Minnesota;

 TITLE = Field Studies of Dependence of Air Infiltration on Outside
Temperature and Wind;
 AUTHOR = Malik, N. J.;
 TYPE = JOURNAL;
   DATE = 04/--/78;
   VOLUME.TITLE = Energy and Buildings;
   VOLUME.NO = 1;
   PAGES = 281-292;
   PUBLISHER.NAME = Elsevier Sequoia;
   PUBLISHER.CITY = Lausanne, Switzerland;

 TITLE = Wind Effect on the Air Movement Inside Buildings;
 AUTHOR = Malinowski, H. K.;
 TYPE = CONF. PROC.;
   DATE = 1971;
   VOLUME.TITLE = Proc. of the third Int. Conf. on Wind Effects on
Buildings and Structures;
   PAGES = 125-134;

 TITLE = The Effectiveness of an Evergreen Windbreak for Reducing
Residential Energy Consumption;
 AUTHOR = Mattingly, G. E.;
 AUTHOR = Harrje, D. T.;
 AUTHOR = Heisler, G. M.;
 TYPE = REPORT;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 85 part 2;
   REPORT.NO = DE-79-1 no. 2;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Interim Report on the Continuous Injection Air
Infiltration Measuring Device;
 AUTHOR = Mencher, P.;
 TYPE = REPORT;
   DATE = 09/--/77;
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 TITLE = Winter Infiltration Through Swinging-Door Entrances in
Multi-Story Buildings;
 AUTHOR = Min, T. C.;
 TYPE = REPORT;
   DATE = 06/--/58;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 64;
   PAGES = 421-446;
   REPORT.NO = 1643;
   PUBLISHER.NAME = ASHRAF;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Net Annual Heat Loss Factor Method for Estimating Heat
Requirements of Buildings;
 AUTHOR = Mitalas, G. P.;
 TYPE = REPORT;
   DATE = 11/--/76;
   REPORT.NO = NRCC 117;
   PUBLISHER.NAME = NRCC;
   PUBLISHER.CITY = Ottawa, Canada;

 TITLE = Air Infiltration Measurements on the Four-Bedroom Townhouse;
 AUTHOR = Peavy, B. A.;
 AUTHOR = Burch, D. M.;
 AUTHOR = Hunt, C. M.;
 AUTHOR = Powell, F. J.;
 TYPE = REPORT;
   VOLUME.TITLE = Building Science Series;
   VOLUME.NO = 57;
   PAGES = 47-50;

 TITLE = Residential Ventilation with Heat Recovery: Improving
Indoor Air Quality and Saving Energy;
 AUTHOR = Roseme, G. D.;
 AUTHOR = Berk, J. V.;
 AUTHOR = Boegel, M. L.;
 AUTHOR = Hollowell, C. D.;
 AUTHOR = Rosenfeld, A. H.;
 AUTHOR = Turiel, I.;
 TYPE = DRAFT;
   DATE = 10/--/79;
   VOLUME.TITLE = TO be published in the procedings of the
DOE/ASHRAE Conference on Thermal Performance of Exterior Envelopes
of Buildings;

 TITLE = Air Infiltration in Buildings:  Literature Survey and
Proposed Research Agenda;
 AUTHOR = Ross, H. D.;
 AUTHOR = Grimsrud, D. T.;
 TYPE = REPORT;
   DATE = 02/--/78;
   VOLUME.TITLE = LBL Report 7822;
   REPORT.NO = LBL-7822;
   PUBLISHER.NAME = Technical Information Department, LBL;
   PUBLISHER.CITY = Berkeley, CA;
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 TITLE = Halogenated Compounds as Gaseous Meteorological Tracers-
Stability and Ultrasensitive Analysis by Gas Chromatography;
 AUTHOR = Saltzman, B. E.;
 AUTHOR = Colemen, A. I.;
 AUTHOR = Clemons, C. A.;
 TYPE = REPORT;
   DATE = 05/--/66;
   VOLUME.TITLE = Analytical Chemistry;
   VOLUME.NO = 38 part 6;
   PAGES = 753-758;

 TITLE = Air Infiltration through Revolving Doors;
 AUTHOR = Schutrum, L. F.;
 AUTHOR = Ozisik, M.;
 AUTHOR = Baker, J. T.;
 AUTHOR = Humphreys, C. M.;
 TYPE = REPORT;
   DATE = 06/--/61;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 67;
   PAGES = 488-506;
   REPORT.NO = 1760;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Air Leakage Measurements of the Exterior Walls of Tall
Buildings;
 AUTHOR = Shaw, C. Y.;
 AUTHOR = Sander, D. M.;
 AUTHOR = Tamura, G. T.;
 TYPE = REPORT;
   DATE = 06/--/73;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 79 part 2;
   PAGES = 40-48;
   REPORT.NO = 2280;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N. Y.;

 TITLE = A Method for Predicting Air Infiltration Rates For a Tall
Building Surrounded by Lower Structures of Uniform Height;
 AUTHOR = Shaw, C. Y.;
 TYPE = REPORT;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 85 part 1;
   REPORT.NO = 2514;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Air Tightness and Air Infiltration of School Buildings;
 AUTHOR = Shaw, C. Y.;
 AUTHOR = Jones, L.;
 TYPE = REPORT;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 85 part 1;
   REPORT.NO = 2515;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;
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 TITLE = The Calculation of Air Infiltration Rates Caused by Wind
and Stack Action for Tall Buildings;
 AUTHOR = Shaw, C. Y.;
 AUTHOR = Tamura, G. T.;
 TYPE = REPORT;
   DATE = 1977;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 83 part 2;
   REPORT.NO = 2459;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = The Energy Cost of Humidification;
 AUTHOR = Shelton, J. W.;
 TYPE = JOURNAL;
   DATE = 01/--/76;
   VOLUME.TITLE = ASHRAE J.;
   VOLUME.NO = 18;
   PAGES = 52-55;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Infiltration-Pressurization Correlation:  Surface
Pressures and Terrain Effects;
 AUTHOR = Sherman, M. H.;
 AUTHOR = Grimsrud, D. T.;
 AUTHOR = Diamond, R. C.;
 TYPE = JOURNAL;
   DATE = 1979;
   VOLUME.TITLE = ASHRAE Trans;
   VOLUME.NO = 85-II;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, NY;
 TYPE = REPORT;
   DATE = 03/--/79;
   VOLUME.TITLE = LBL Report-8785;
   REPORT.NO = LBL-8785;
   PUBLISHER.NAME = Technical Information Department, LBL;
   PUBLISHER.CITY = Berkeley, CA;

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 TITLE = The Low Pressure Leakage Function of a Building;
 AUTHOR = Sherman, M. H.;
 AUTHOR = Grimsrud, D. T.;
 AUTHOR = Sonderegger, R. C.;
 TYPE = REPORT;
   DATE = 11/--/79;
   VOLUME.TITLE = LBL Report 9162;
   REPORT.NO = LBL-9162;
   PUBLISHER.NAME = Technical Information Department, LBL;
   PUBLISHER.CITY = Berkeley, CA;
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●  TITLE = Wind, Temperature and Natural Ventilation-- Theoretical
  Considerations;
   AUTHOR = Sinden, F. W.;
   TYPE = JOURNAL;
     DATE = 04/--/78;
     VOLUME.TITLE = Energy and Buildings;
     VOLUME.NO = 1;
     PAGES = 275-280;
     PUBLISHER.NAME = Elsevier Sequoia;
     PUBLISHER.CITY = Lausanne;

●  TITLE = Analysis of Infiltration by Tracer Gas Technique,
  Pressurization Tests, and Infrared Scans;
   AUTHOR = Stewart, M.;
   AUTHOR = Jacob, T. R.;
   AUTHOR = Winston, J. G.;
   TYPE = DRAFT;
     DATE = 1979;
     VOLUME.TITLE = to be published in  Procedings of DOE/ASHRAE
   Conference on Thermal Performance of buildings;

●  TITLE = Measurement of Air-Tightness of Houses;
   AUTHOR = Stricker, S.; /
   TYPE = REPORT;
     DATE = 01/--/75;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 81 part 1;
     PAGES = 148-167;
     REPORT.NO = 2336;
     PUBLISHER.NAME = ASHRAE;
     PUBLISHER.CITY = New York, N.Y.;

●  TITLE = Measurement of Air Leakage Characteristics of House
  Enclosures;
   AUTHOR = Tamura, G. T.;
   TYPE = REPORT;
     DATE = 01/--/75;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 81 part 1;
     PAGES = 202-211;
     REPORT.NO = 2339;
     PUBLISHER.NAME = ASHRAE;
     PUBLISHER.CITY = New York, N.Y.;

   TITLE = Studies on Exterior Wall Air Tightness and Air
  Infiltration of Tall Buildings;
   AUTHOR = Tamura, G. T.;
   AUTHOR = Shaw, C. Y.;
   TYPE = REPORT;
     DATE = 02/--/76;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 92 part 1;
     PAGES = 122-134;
     REPORT.NO = 2388;
     PUBLISHER.NAME = ASHRAE;
     PUBLISHER.CITY = New York, N.Y.;
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   TITLE = The Calculation of House Infiltration Rates;
   AUTHOR = Tamura, G. T.;
   TYPE = REPORT;
     DATE = 01/--/79;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 85 part 1;
     REPORT.NO = 2513;
     PUBLISHER.NAME = ASHRAE;
     PUBLISHER.CITY = New York, N.Y.;

   TITLE = Pressure Differences for a Nine-Story Building as a Result
  of Chimney Effect and Ventilation System Operation;
   AUTHOR = Tamura, G. T.;
   AUTHOR = Wilson, A. G.;
   TYPE = REPORT;
     DATE = 01/--/66;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 72;
     PAGES = 180-189;
     REPORT.NO = 1973;
     PUBLISHER.NAME = ASHRAE;
     PUBLISHER.CITY = New York, N.Y.;

●  TITLE = Air Leakage and Pressure Measurements on Two Occupied
  Houses;
   AUTHOR = Tamura, G. T.;
   AUTHOR = Wilson, A. G.;
   TYPE = REPORT;
     DATE = 01/27/64;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 70;
     PAGES = 110-119;
     REPORT.NO = 1869;
     PUBLISHER.NAME = ASHRAE;
     PUBLISHER.CITY = New York, N.Y.;

●  TITLE = Analysis of Smoke Shafts for Control of Smoke Movement in
  Buildings;
   AUTHOR = Tamura, G. T.;
   TYPE = REPORT;
     DATE = 06/28/70;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 76;
     PAGES = 290-297;
     REPORT.NO = 2163;
     PUBLISHER.NAME = AHSRAE;
     PUBLISHER.CITY = New York, N.Y.;

●  TITLE = Computer Analysis of Smoke Movement in Tall Buildings;
   AUTHOR = Tamura, G. T.;
   TYPE = REPORT;
     DATE = 06/--/69;
     VOLUME.TITLE = ASHRAE Trans.;
     VOLUME.NO = 75;
     PAGES = 81-92;
     REPORT.NO = 2114;
     PUBLISHER.NAME = ASHRAE;
     PUBLISHER.CITY = New York, N.Y.;
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 TITLE = Condensation Problems in Flat Wood-Frame Roofs;
 AUTHOR = Tamura, G. T.;
 AUTHOR = Kuester, G. H.;
 AUTHOR = Handegord, G. O.;
 TYPE = REPORT;
   DATE = 09/--/74;
   REPORT.NO = NRCC 14589;
   PUBLISHER.NAME = National Research Council Canada;
   PUBLISHER.CITY = Ottawa, Canada;

 TITLE = Natural Venting to Control Smoke Movement in Buildings Via
Vertical Shafts;
 AUTHOR = Tamura, G. T.;
 AUTHOR = Wilson, A. G.;
 TYPE = REPORT;
   DATE = 07/--/70;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 76;
   PAGES = 279-289;
   REPORT.NO = 2162;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Building Pressures Caused by Chimney Action and Mechanical
Ventilation;
 AUTHOR = Tamura, G. T.;
 AUTHOR = Wilson, A. G.;
 TYPE = REPORT;
   DATE = 06/--/67;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 73;
   PAGES = II.2.1-II.2.12;
   REPORT.NO = 2047;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Pressure Differences Caused by Wind on Two Tall Buildings;
 AUTHOR = Tamura, G. T.;
 AUTHOR = Wilson, A. G.;
 TYPE = REPORT;
   DATE = 06/--/68;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 74;
   PAGES = 170-181;
   REPORT.NO = 2085;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Pressure Differences Caused by Chimney Effect in Three
High Buildings;
 AUTHOR = Tamura, G. T.;
 AUTHOR = Wilson, A. G.;
 TYPE = REPORT;
   DATE = 06/--/67;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 73;
   PAGES = II.1.1-II.1.10;
   REPORT.NO = 2046;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;
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TITLE = The Thermal Performance of a Two-Bedroom Mobile Home;
AUTHOR = Teitsma, G. J.;
AUTHOR = Peavy, B. A.;
TYPE = REPORT;
  DATE = 01/--/77;
  REPORT.NO = NBSIR 76-1182;
  PUBLISHER.NAME = Federal Energy Administration;
  PUBLISHER.CITY = Washington, D.C.;

TITLE = Sulfur Hexafluoride as a Gas-Air Tracer;
AUTHOR = Turk, A.;
AUTHOR = Edmonds, S. M.;
AUTHOR = Mark, H. L.;
AUTHOR = Collins, G. F.;
TYPE = REPORT;
  DATE = 01/--/68;
  VOLUME.TITLE = Environmental Science and Technology;
  VOLUME.NO = 2 part 1;

TITLE = Contaminant Dispersion and Dilution in a Ventilated Space;
AUTHOR = West, D. L.;
TYPE = REPORT;
  DATE = 1977;
  VOLUME.TITLE = ASHRAE Trans.;
  VOLUME.NO = 83 part 1;
  PAGES = 125-140;
  REPORT.NO = 2437;
  PUBLISHER.NAME = ASHRAE;
  PUBLISHER.CITY = New York, N.Y.;

TITLE = Evaluation of Window Performance;
AUTHOR = Wilson, A. G.;
AUTHOR = Sasaki, J. R.;
TYPE = REPORT;
  DATE = 05/02/72;
  VOLUME.TITLE = Nat. Bur. Stand. Special Publication 361;
  VOLUME.NO = 1;
  PAGES = 385-394;
  PUBLISHER.NAME = NRCC;
  PUBLISHER.CITY = Ottawa, Canada;

TITLE = Influence of the House on Chimney Draft;
AUTHOR = Wilson, A. G.;
TYPE = REPORT;
  DATE = 02/13/61;
  VOLUME.TITLE = ASHRAE Trans.;
  VOLUME.NO = 67;
  PAGES = 317-329;
  REPORT.NO = 1749;
  PUBLISHER.NAME = ASHRAE;
  PUBLISHER.CITY = New York, N.Y.;
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 TITLE = Convective Air Flow Effects with Mineral Wool Insulation
in Wood-Frame Walls;
 AUTHOR = Wolf, S.;
 AUTHOR = Solvason, K. R.;
 AUTHOR = Wilson, A. G.;
 TYPE = REPORT;
   DATE = 06/27/66;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 72;
   PAGES = III.3.1 - III.3.8;
   REPORT.NO = 2003;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = A Theory for the Effects of Convective Air Flow through
Fibrous Thermal Insulation;
 AUTHOR = Wolf, S.;
 TYPE = REPORT;
   DATE = 06/27/66;
   VOLUME.TITLE = ASHRAE Trans.;
   VOLUME.NO = 72;
   PAGES = III.2.1 - III.2.9;
   REPORT.NO = 2002;
   PUBLISHER.NAME = ASHRAE;
   PUBLISHER.CITY = New York, N.Y.;

 TITLE = Ventilation Requirements (part 2);
 AUTHOR = Yaglou, C. P.;
 AUTHOR = Witheridge, W. N.;
 TYPE = REPORT;
   DATE = 06/--/37;
   VOLUME.TITLE = ASHVE Trans.;
   VOLUME.NO = 43;
   PAGES = 423-436;
   REPORT.NO = 1068;
   PUBLISHER.NAME = ASHVE;

 TITLE = Ventilation Requirements;
 AUTHOR = Yaglou, C. P.;
 AUTHOR = Riley, E. C.;
 AUTHOR = Coggins, D. I.;
 TYPE = REPORT;
   DATE = 01/--/36;
   VOLUME.TITLE = ASHVE Trans.;
   VOLUME.NO = 42;
   PAGES = 133-162;
   REPORT.NO = 1031;
   PUBLISHER.NAME = ASHVE;
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