Air Infiltration in Buildings: Literature Survey and Proposed Research Agenda

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EXECUTIVE SUMMARY

Air infiltration in buildings is defined as the uncontrolled leakage of air through cracks and openings in the building envelope. This mass transfer of air is driven by weather (in particular, indoor-outdoor temperature differences and wind velocity) and is a function of the building architecture, occupant activity, and topological location (siting). Air infiltration accounts for 20-50 percent of the heating load of residential structures. Commercial buildings are usually maintained at a positive pressure relative to the outdoors, which reduces infiltration to a great extent but increases energy consumption and cost. Due to the impact of air infiltration on building energy consumption, members of the International Energy Agency (IEA) have expressed interest in establishing research priorities in air infiltration.

In the past 30 years, international research has been conducted primarily on residences to understand air infiltration, and especially to model or predict infiltration rates in order to improve the design of buildings and to properly size mechanical equipment. Although the research is extensive, certain phenomena require further study: exterior wall leakage characteristics are very poorly understood; dynamic effects, such as pulsating flow, eddies, and turbulent flows through multiple cracks, have only recently undergone any examination; and the effect of moisture on crack size is not understood well enough to be incorporated into any mathematical model. Investigations in the past have been somewhat restricted by measurement instrumentation, and models have been primarily empirical. Traditionally, models of residential buildings have taken the form of:

$$INF = A + B \cdot \Delta T^m + CW^n$$

where INF is the infiltration rate, ΔT is indoor-outdoor temperature difference, W is wind speed, A, B, and C are regression coefficients, and m and n are arbitrarily-selected exponents. This form of analysis reveals that specific correlations with weather variables have only been moderately successful. Because the regression coefficients reflect structural characteristics as well as shielding effects and occupant behavior, the respective values of A, B, and C have varied by 20:1 between similar residences, and the model may be inappropriate as a design tool or for inclusion in computer simulations for building energy analysis. Recent work has improved the traditional model by including an approximation of the crackage of the house:

$$INF = \beta_O \cdot C_T \sqrt{4 \cdot \Delta P_T + \sqrt{2 \cdot \Delta P_W}}$$

where INF = infiltration rate

β_O = regression coefficient

C_T = equivalent crack length

ΔP_T = pressure difference due to stack effect or

= $A \cdot P \cdot h\ (1/T_i - 1/T_o)$ and A = constant, P = absolute pressure,

h = height of the neutral zone, T_i = inside temperature,

T_o = outside temperature

ΔP_W = pressure difference due to wind speed or

= BW^2/T_o, and B = constant.

Infiltration rates upon which these models have been based are determined by measurement techniques using a tracer gas. The tracer gas is injected into the interior of an entire structure and mixed until uniform gas concentration is achieved; various methods then are used to monitor the concentration decay rate due to air infiltration. The decay rate can be related to air infiltration rates directly.

This measurement technique has been developed and used extensively for residential structures, but it has been attempted for commercial structures on an extremely limited basis. A few commercial building models have been developed on a theoretical basis or as a result of wind-tunnel scale experiments and field studies using pressure reading instruments. Canadian researchers have developed complex physically-based algorithms for a restricted class of high-rise buildings (constant cross-sectional area, curtain wall construction sealed windows, office functions). These algorithms are attractive because they can be coupled to existing hour-by-hour computer simulations. At this time, however, the algorithms have not been field validated using tracer-gas techniques. Also, user judgment is required to select values for a number of variables in the algorithms, and the data base upon which to make the selection is weak.

A limited amount of work has been conducted in the area of open windows in regard to user motivation, measured infiltration rates, and modeling of effects on energy consumption. Given the state-of-the-art of modeling techniques for closed windows and the lack of sufficient data on measured infiltration rates through open windows, a physically-based model for open window infiltration appears to be a substantial endeavor which may require a long-term effort.

A great amount of research is required to address all of the questions surrounding the physical phenomena of air infiltration. We recommend beginning a number of projects immediately. These recommendations are based on preliminary indications of IEA participants' interest and on anticipated near-term return of results:

(1) We recommend the establishment of a centralized data management center to transfer data between researchers, and to perform in-house cross-checks of results. One initial activity of this center could be to look at

particular existing models using previously assembled data and assess their validity in structures other than the buildings upon which the models were originally calibrated.

(2) Infiltration rates should be measured using tracer gas techniques at selected sites in order to validate the commercial building algorithms developed by Canada researchers and others. The selection of buildings should be compatible with the test cases modeled by the developers of the algorithms, and then move progressively toward more complex geometries, functions, and building materials.

(3) Correlation of air infiltration rates with leakage rates from pressurization tests should be attempted in selected residences to improve our ability to incorporate the physical characteristics of structures into computer models. In addition, micro-climate pressure data should be gathered to determine flow patterns around each structure and to quantify external shielding effects in the field. External shielding effects are best realized through air-exchange measurement and correlation with building surroundings. The external shielding effects on air infiltration should be the primary research effort, not the detailed complex flow patterns around the building.

(4) Measurement of air infiltration rates through open windows, as well as observations of occupancy behavior, should continue as a first step toward characterizing a probability function for air infiltration rates under certain weather conditions, structural geometrics, and occupancy conditions.

1.0 INTRODUCTION

England is a cosy little country,
Excepting for the draughts along the floor,
And that is why you're told
When the passages are cold
Darling, you've forgot to shut the door!
Rudyard Kipling

Air infiltration, the uncontrolled leakage of air through cracks and openings in a building envelope, contributes significantly to energy consumption required to maintain an acceptable environment within a building. Field studies have revealed that infiltration may represent between 20-50 percent of the building's heating load. In commercial buildings, Tamura and Shaw (Canada) have established that the additional energy consumption due to pressurization, the most common method of overcoming infiltration, may in fact cause a tripling of the ventilation heating load relative to uncontrolled leakage.

Analysis of the infiltration phenomena has been attempted extensively over the last 30 years. The mechanisms and driving potentials by which infiltration occurs are not adequately understood. With the advent of computerized building energy analysis techniques, accurate analytical modeling of infiltration has become increasingly important. Modeling is the weakest link in the loads' analysis portion of the simulations and remains a complex phenomena for which few physical models have been developed. In an unpublished report by Ohio State University (United States), 15 significant parameters required for analysis were cited with the disclaimer that this list is by no means definitive:

(1) Indoor-outdoor temperature difference

(2) Wind speed - instantaneous versus integrated, local versus actual at cracks

(3) Wind direction - instantaneous versus integrated, orientation of house

(4) Neutral zone - location, how it changes

(5) Chimneys - alternate path or additive

(6) Cracks - length, width, and location

(7) Gas versus electric - combustion air make-up

(8) Door openings - duration, wind effects

(9) Exhaust fan operation - duration

(10) Interaction of temperature and wind effects

(11) Air infiltration paths within the structure

(12) Wind effects - broad side, wind breakers

(13) Construction - materials, craftmanship

(14) Porosity - exterior walls, ceilings

(15) Steady-state assumptions versus pulsation and eddies.

Based on a literature review of primarily North American documents, and upon some written notes from Bo Adamson (Sweden) and Peter Hartman (Switzerland), the authors have found that several areas necessary for understanding the best means of simulating infiltration of any particular building type remain controversial or unaddressed.

Simulation Time Scale

Traditionally, calculation procedures for infiltration have been established for estimates of design heating loads. Within the past 10 years, algorithms have been developed which attempt to predict hourly infiltration values based on a steady-state analysis. However, recent work conducted by Hill and Kusuda and by Malinowski suggests that the hourly time step and the steady-state approach do not adequately address the dynamic characteristics of infiltration caused by pulsating flow, eddies, or turbulent flows through cracks in the building envelope. The apparent conclusion that can be drawn from this work is that the physics of the infiltration phenomena would be more appropriately analyzed and modeled with the use of a time step significantly shorter than 1 hour. Researchers at Princeton University believe that the local interactive effects of the multiple parameters affecting air infiltration will never adequately be addressed, and that a much longer time step, or an average infiltration value for certain building geometries, will suffice.

Weather Correlation and Driving Potentials

The existing state-of-the-art modeling procedures utilize two weather parameters: indoor-outdoor dry-bulb temperature differences and wind velocity (speed and direction) as the sole weather-related driving potential for infiltration. The relative importance and interdependence of each of these parameters are still unclear. Variances of 20:1 in individual regression coefficients* have been found from investigations of similar structures, with the constant term having either a positive or negative value.

Many authors have also suggested that the wind direction is not required for modeling, based upon statistical analysis of field data and the physical interpretation that cracks around a building envelope are uniformly distributed. More recent studies claim that improved correlation coefficients are obtained by including wind direction as a parameter, and that its inclusion also helps to explain shielding effects by external wind barriers.

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* Typical models have taken the form: $INF = A + B \Delta T^{\alpha} + C \cdot W^{\gamma}$; where A, B, and C are regression coefficients, ΔT is the temperature difference, and W is the wind speed. α is usually between 1 and 2; γ usually between 1/2 and 1.

In addition to these parameters, other variables may necessarily be required in an infiltration algorithm based on weather. It is known that moisture additions can expand wood, thus reducing the crack size, and that solar radiation, heating the outside surfaces of a building, may affect the expansion of metal window frames significantly, also reducing crack size.*

In addition to the weather-related variables, some authors have claimed tha user-influenced parameters such as door openings and combustion-induced infiltration must be accounted for in infiltration models. In general, this concern has developed from attention to the constant term in many of the infiltration models; many people have expressed skepticism about the existence of such a term in the absence of external driving potentials (zero indoor-outdoor temperative difference, zero wind velocity). The nature of this term remains unclear. One conclusion that can be drawn at this point is that an algorithm for prediction of infiltration rates can not be solely dependent on statistical analysis of weather-related correlations; it must also take into account the physical parameters of a structure.

Physical Structure Correlations

Three traditional approaches have been taken toward infiltration rate prediction in the U.S.:

- Based on wind speed, a pressure difference across windows is determined, from which an infiltration rate per length of crack is established (ASHRAE crack length method).
- A constant value of air infiltration rate is assigned to a room after consideration of location, and number of windows and doors (ASHRAE air change method).
- The original or modified Achenbach-Coblentz correlation, which has no tie to the physical parameters of the structure. Hartmann has made modifications to include a factor for space location, and others have included "an equivalent orifice coefficient."

Physically-based algorithms and field experiments have not adequately addressed the following questions:

- Where, and how critical, is the location of the neutral pressure zone? How time-dependent (with occupancy involved) is this parameter?

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* This phenomena also points to the need for time-dependent analysis infiltration or at least a different model for day and night conditions.

- What is the effect of recessed windows, typical in commercial buildings, on air infiltration?

- Is there a correlation between leakage area measured using pressurization/evacuation techniques and air infiltration values?

- Is it possible to generate a normalization coefficient which accounts for differences in the surface/volume characteristics of various structures?

- It is suspected that significant convection occurs through some insulating materials (e.g. fiberglass), thus establishing alternate pathways for air migration, and contributing to the stack effect. How can this phenomena be quantified?

User Influences

Easily the most important physical contribution to total air infiltration is the effect of open windows, which can affect air infiltration by orders of magnitude. Traditional U.S. models have not attempted any accounting of the user influence on air infiltration paths. European algorithms (Hartmann, Dick) have attempted to include this parameter, Canadian models (Tamura-Shaw) have shown that the effect of a single opening per exposure can be included for high-rise buildings, but do not attempt to predict when any numbers of windows may be open.

The first question that must be asked is "What is the probability of X windows being open at any time?" In order to make any prediction, observations of occupancy habits must be made. However, a prior question remains: what parameters are important in determining the user's activity (temperature, season, ambient noise, location, outdoor pollution, etc.)?

Other broad questions remain regarding the infiltration problem, such as the number of separate models needed for a variety of building types. The authors suggest that models must be developed for each broad classification of structures (e.g., residential, low-rise, high-rise) for which the air buoyancy behavior differs substantially.

Many of the forementioned questions are oriented toward small residential buildings, but they are generally applicable to larger buildings, also. The few physical models available for larger buildings remain unvalidated. The literature survey summary in the next section reveals that most of the research has been in residential applications. Commercial buildings present special concerns and specific projects for validating state-of-the-art algorithms and for improving the data base on air infiltration needed to calibrate some of the required variables are described in the next section.

2.0 LITERATURE SURVEY SUMMARY

This literature survey was conducted to investigate the research that addresses some key technical questions about air infiltration. These questions are the appropriate time scale, weather correlations and driving potentials, physical structure correlations, and user influence.

Time Scale

The appropriate time scale of measurements of infiltration has not been considered often in the literature. Typically, the rate of measuring air infiltration has been limited by the instrumentation used. For example, the time required to determine the slope of tracer gas decay concentration curves places an upper bound on the rate of change of infiltration that can be measured using this method. However, one can examine the problem from another point of view -- the time scale associated with the driving mechanisms of the infiltration process.

Hill and Kusuda (1975) have examined the mechanisms of infiltration due to wind and show that pulsating flow (e.g., flow through a single opening in a room when the rest of the room is sealed) can lead to a significant air exchange because of the turbulence created near the opening.

Cockroft and Robertson (1976) investigated turbulent mixing of outdoor and indoor air due to fluctuating components of the wind. Their model experiments suggest that one-third of the fluctuating air flow into an enclosure through a single opening is mixed with the bulk air in the volume and therefore contributes to the infiltration rate. Warren (1977) has investigated the mechanisms leading to ventilation through openings in just one wall. His results indicate that temperature differences and mean pressure differences across walls where more than one opening is present are more important for natural ventilation than turbulent diffusion or the interaction of a projecting casement window with the local air flow.

The important frequencies of power spectrum of temperature differences are much lower. The dominant period, of course, is the 24-hour period associated with daily solar insolation. Sonderegger (1977) has shown that the amplitude of the outside temperature cycle with a period of 4 hours (the sixth harmonic) is smaller than the amplitude of the dominant 20-hour period by a factor of 30. Significant outdoor temperature fluctuations with periods shorter than 4 hours are not easily observable.

Weather Correlations and Driving Potentials

Questions of driving mechanisms for infiltration and weather correlations used to link infiltration measurements to existing conditions are clearly bound together. Modeling infiltration may be done by assuming simple regression formula such as:

$$INF = A + BW + C \cdot \Delta T$$

where INF is the air infiltration, W is the wind speed, ΔT is indoor-outdoor temperature difference, and A, B, and C are constants obtained from regression analysis.

The analysis may also start by physically modeling the infiltration process. The proper characterization of the properties of the structure (crack size and distribution of openings), which vary widely in different structures, and is an extremely difficult problem.

Dick and Thomas (1951) measured infiltration in 20 homes in Abbots Langley and 8 in Bucknalls Close in Great Britain. The 20 Abbots Langley sites were exposed (mean wind speed 14 km/h) and the effect of the wind on infiltration dominated the results. These were represented by:

$$INF = A + B \cdot W + C(n + 1.4m) + D \cdot W \cdot (n + 1.4m),$$

where m and n represent the mean number of casement windows and open vents, respectively.

In the Bucknalls Close site, which was sheltered (mean wind speed 7 km/h), two expressions were used to represent the results:

$$INF = (A + Bn) \cdot W, \text{ when the value of } W^2/\Delta T > 14 \frac{(km/h)}{^{\circ}C} \text{ and}$$

$$INF = (C + Dn) \cdot (\Delta T)^{1/2}, \text{ when } \frac{W^2}{\Delta T} < 14 \frac{(km/h)}{^{\circ}C}$$

where A, B, C, and D are constants determined by statistical analysis.

Note that a constant term exists in the expression developed to represent the Abbots Langley results while it is missing from the Bucknalls Close results. Dick and Thomas suggest that the constant term is the result of the heating systems used in the houses of Abbots Langley. The houses of Bucknalls Close were heated with hot water radiators or ceiling hot water panels. The hot water boilers were not located in the house.

Bahnfleth, Mosley, and Harris (1957) measured infiltration in two research houses in Illinois (USA). Both houses contained furnaces -- one heated water for a hot water heating system; the second a gas-fired forced air system. Both sets of data can be represented by:

$$INF = A + B \cdot W + C \cdot \Delta T.$$

The constants A, B, and C are determined from graphical representations, and they differ significantly for the two houses. For example, if one assumes a 16.1 km/h wind and a 64.4 km/h wind, the infiltration is 0.40 air changes per hour and 0.52, respectively. Bahnfleth, Mosley, and Harris suggest that the constant term in their expression for infiltration may be due to their measurement technique. They used helium as the tracer gas; they conjecture the gas may have diffused through the walls of the test structure. Therefore, non-zero infiltration will be indicated even when no infiltration occurs.

Coblentz and Achenbach (1963) measured infiltration in 10 electrically-heated houses in Indiana (USA). Their work did not include enough measurements to calibrate an infiltration model relating their measurements to weather parameters. Therefore they adopted the regression model of Bahnfleth, Mosley, and Harris (1957) to reduce the data to standard conditions of wind speed (16.1 km/h) and temperature difference (22.2^{o} C). One interesting feature of this paper is the comment by Harris of the University of Illinois in the discussion following the paper. He points out that the constants A, B, and C in the regression analysis expression:

$$INF = A + B \cdot W + C \cdot \Delta T$$

are structure related and are determined primarily by the quality of construction. Therefore an infiltration model which is determined for one house cannot be used with the same constants for another house.

Laschober and Healy (1964) measured infiltration in two houses in Illinois (USA). One was heated using a hot water distribution system, the other a gas- and electric-fired forced-air system. The authors used many different regression models to attempt to relate infiltration measurements to weather parameters. Statistically, the best fit of their data came from the expressions:

$$INF = A + B \cdot W_L + C \cdot \Delta T \text{ for house 1 and}$$

$$INF = A' + B' \cdot W_L + C' \cdot \Delta T + D' \cdot EG \text{ for house 2.}$$

Again, A, B, C, A', B', C', and D' are constants, INF represents the infiltration, and ΔT, the indoor-outdoor temperature difference. Two new terms were found to be statistically significant. W_L is the wind component striking the long side of a rectangular house. This component is found by multiplying the wind speed by the cosine of the angle between the wind direction and normal to the wall. EG takes on different integer values (+1, -1) for gas or electric furnaces. No interpretation is given for the constant terms A and A'. (A', in fact, is negative and has a value of -0.2734 air changes per hour.) The authors comment that the two houses were not as airtight as those measured previously by Bahnfleth, Mosley, and Harris.

Tamura and Wilson (1964) measured infiltration in two Canadian houses. Both were single-story houses heated with oil-fired, warm-air furnaces. Their measurements showed that (a) infiltration was proportional to wind speed, a result determined in summer measurement when ΔT was small, (b) infiltration was proportional to $(\Delta T)^{1/2}$, a result obtained when the wind speed was low, and (c) that infiltration was affected by furnace action. In addition, they found that infiltration "components" were not additive. That is, the infiltration due to the wind speed W_o when $\Delta T = 0$ and the infiltration due to the temperature difference ΔT_o when $W = 0$ cannot be added together to give the infiltration when the wind speed is W_o and the temperature difference is ΔT_o.

Howard (1966) measured natural ventilation in rooms in six single-story detached houses in Melbourne, Australia. Because indoor-outdoor temperature differences were small, this influence was not seen in the measurements. Ventilation rate was found to be proportional to wind speed but influenced by wind direction and chimney openings. Ventilators above windows were perceived to be of little value in accomplishing their design task of natural ventilation.

Elkins and Wensman (1971) measured infiltration in two occupied houses in Ohio (USA). One used gas heat; the other, electricity. Temperature effects were not important in the analysis of the data. The measured infiltration could be explained statistically with an expression of the form:

$$INF = (A - B \cdot \Theta)W \text{ for house 1 and}$$

$$INF = (A' - B' \cdot \Theta)W \text{ for house 2.}$$

A, A', B, and B' are all positive constants; INF and W are infiltration rates and wind speed, respectively; and Θ is the angle between the normal to the long wall of the house and the wind direction.

Hunt and Burch (1975) measured air infiltration in a four-bedroom townhouse enclosed in an environmental chamber. Therefore, all wind-induced infiltration mechanisms were eliminated from the study. The results of their measurements could be represented in two ways. Either as:

$$INF = A + B \cdot \Delta T \text{ or as}$$

$$INF = C \cdot (\Delta T)^{1/2}.$$

The latter expression is consistent with the model for temperature-driven infiltration (stack effect) presented in the ASHRAE Handbook of Fundamentals. The data presented in the paper include only measurements made when ΔT is greater than 5.6^{o} C. The common question of whether infiltration vanishes in this house as ΔT goes to zero was not settled.

A Hittman Associates report (1975) models infiltration in houses using the same linear form as that given in many papers above:

$$INF = A + B \cdot W + C \cdot \Delta T.$$

Coefficients A, B, and C are given for a "typical" house. This expression is used to model infiltration in order to determine energy use in the structure. The coefficients, in turn, were determined by modeling theoretical infiltration processes across walls of buildings. The constant term A, represents air infiltration when ΔT and W are zero. The report suggests that it is the result of:

- opening and closing doors and windows,
- operating ventilation fans in kitchens and bathrooms,
- using hot water heater, gas clothes dryer, and furnace.

The terms B and C were chosen by using the results of a model calculation of infiltration. This model uses an estimate of the crack distribution for a house; calculates the pressure distribution of particular cracks due to wind and temperature differences; and estimates the infiltration that results. This procedure leads to values of infiltration which are not linearly related to wind speed and temperature differences. The non-linearity, however, is not severe. Thus, B and C are chosen to yield a linear approximation for the infiltration model.

Sinden (1976b) presents strong theoretical arguments showing that the effects of wind and temperature difference should not be additive when considering infiltration driven by both effects. He makes assumptions about airflow through a single point on a wall, then shows that these assumptions lead to the subadditive property for the entire building which is defined below. Flow through a point Z on a wall driven by a pressure difference Δp is represented by $a(Z, \Delta p)$. Then, if the following assumptions are true:

(1) $a(Z, \Delta p)$ always has the same sign as Δp and

$a(Z, 0) = 0$,

(2) $a(Z, \Delta p)$ is monotonic with respect to Δp: $\Delta p_1 > \Delta p_2$

implies that $a(Z, \Delta p_1) > a(Z, \Delta p_2)$, and

(3) $a(Z, \Delta p)$ is subadditive with respect to Δp:

$$a(Z, \Delta p_1 + \Delta p_2) \leq a(Z, \Delta p_1) + a(Z, \Delta p_2)$$

If $a(Z, \Delta p) = K(\Delta p)^{\alpha}$ where K is some constant and α is less than or equal to one, then a $(Z, \Delta p)$ is subadditive. For air flow through cracks, α ranges between ½ and 1; a value of $\alpha = 2/3$ is commonly used (Sasaki and Wilson, 1965).

Sinden then shows that these assumptions lead to the conclusion that INF $(W, \Delta T) \leq$ INF $(0, \Delta T)$ + INF $(W,0)$, where INF $(W, \Delta T)$ is the total infiltration into a building when the outside wind speed is W and the temperature difference is ΔT.

Luck and Nelson (1977) point out another weather influence which becomes especially important in cold climates. They found from measurements on a one-story house in Minnesota (USA) that the relative humidity which is present in the house has a major influence on infiltration rate. Their results show a decrease in the infiltration rate in the structure by a factor of 2 to 3 as the relative humidity in the structure increases. They attribute this to the swelling of the wood parts of doors, windows, and walls, which result in a decrease in crack size.

Malik (1977) describes air infiltration measurements made in two houses that are part of the Twin Rivers Town House study that Princeton University (USA) has been engaged in for five years. Malik examines several ways to represent his data -- he concludes that several effects are statistically significant. In low wind speed regions ($W < 9.7$ km/h), his results show that for one house:

$$INF = A^* + B^* W|\cos(\theta - \theta_o)| + C^* \Delta T + D^* G + E^* B + F^* F$$

Where A* through F* are regression constants, θ is the direction of the wind, θ_o is the direction of the normal to the back wall of the house, G is the gas consumption, B is fraction of time the basement door is open, and F is the fraction of time the front door is open. Data for the second house are not as complete because information about door openings and gas consumption is needed. This house is represented by:

$$INF = A' + B' \cdot \Delta T$$

where A' and B' are constants appropriate for this house.

In areas of high wind speed, the results for the first house are best represented by:

$$INF = A^* + B^* \cdot \Delta T \cdot W \cdot |\cos(\theta - \theta_o)| + C^* \cdot G + D^* \cdot B \cdot \Delta T.$$

Here A*, B*, C*, and D* are regression coefficients and the variables have been defined above.

Two things are particularly noteworthy about this result: It represents a considerably different form than the previous linear relations, and it indicates a directional dependence to the effect of the wind. In the case of a row of townhouses, this latter effect is not surprising. A physical interpretation of the interaction time between the wind and the temperature would, however, be useful.

Physical Structure Correlations

The standard techniques used to compute expected air infiltration in a building are the crack length method described in Chapter 21 of the 1977 ASHRAE Handbook of Fundamentals and section A4 of the 1970 IVHE Guide Book A. Many authors have compared measured values of air infiltration with calculated values based upon the handbook algorithms and the results vary widely. The reasons for the variation are well understood. In part, the discrepancies can be attributed to large variations in window flow rate (Sasaki and Wilson, 1965). In addition many leakage paths are difficult to identify (Tamura, 1975). Therefore, the problem of characterizing a standard leakage of a building is important and merits particular attention.

Honma (1976) made a large number of laboratory measurements of flow through cracks to examine the nature of the flow as the dimensions of the crack change. His results can be summarized by an empirical relationship he found for the exponent β in the flow relation:

$$Q \doteq \alpha \ \ell \ (\Delta p)^{1/\beta}$$

where Q is the volume flow rate through the crack, α is a proportionality constant for the gap, ℓ is the length of the crack, and Δp is the pressure difference causing the flow. Honma reports that β can be represented:

$$\beta = 2.0 - \exp(-5 \ \alpha \ \Delta p)$$

when Δp and α are expressed in metric units. If the flow through the crack was laminar, $\beta = 1.0$; if full turbulence exists, $\beta = 2.0$.

The routine of Shaw and Tamura (1977) for high-rise structures and that of Sepsy, Jones, McBridge, and Blancett (1977) for single-family homes and low-rise apartments also rely on a structural leakage factor which, without better information, is a subjective estimate of a building's leakage. A simple measurement process is needed to characterize a building's leakage. Perhaps the work of Tamura (1975) or that of Graham and Card (1977) will point to a solution.

The most extensive study of residential infiltration has recently been completed at Ohio State University (USA). This study (Sepsy, Jones, McBride, and Blancett) will be published late in 1977 as a report of the Electric Power Research Institute (EPRI). The OSU/EPRI study examined infiltration in nine homes in Ohio (USA). Almost 2,000 hours of infiltration data were collected, and a very thorough statistical analysis of the data set was performed.

After many regression analyses were generated; several models based upon standard physical driving mechanisms were examined. The authors found that their data could be represented best by:

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

where $\Delta P_T = A \cdot P \cdot h \, (1/T_o - 1/T_i)$

and $\Delta P_W = B/T_o \cdot W^2.$

In this expression, β_o is a statistical regression coefficient (which essentially describes the construction quality of the house); A and B are constants which depend upon the system of units used; P is the absolute pressure; h is the height of the neutral zone in the house; C_T is the total equivalent crack length for the house; T_o is the outside temperature; T_i is the inside temperature; and W is the wind speed. This representation is a significant improvement for it suggests that by determining a single regression coefficient, β_o in this case, and measuring the effective crack length of the house, the infiltration can be modeled through an entire heating season.

Although the research is not as extensive as in residential units, commercial buildings have also been studied. Tamura and co-workers in Canada have made extensive studies of high-rise office buildings during the past 12 years (Tamura and Wilson, 1966, 1967a, 1967b, 1968; Shaw, Sander, and Tamura, 1973; Tamura and Shaw, 1976b). The results of these studies are summarized in the recent paper by Shaw and Tamura (1977). They present an expression for infiltration into a high-rise building driven by both wind pressure and temperature difference. These two effects are not additive, but are combined as shown below:

$$INF_{W,\,\Delta T} = INF_L \cdot \left[1 + 0.24 \left(\frac{INF_S}{INF_L}\right)^{3.3}\right]$$

where $INF_{W,\,\Delta T}$ is the total infiltration; INF_L is the larger of the two infiltration sources and INF_S is the smaller.

Closed form expressions for infiltration as a result of wind and as a result of temperature difference are also given. Infiltration caused by wind depends upon the direction of the wind, a flow coefficient for the wall leakage characteristics, the length of the wall, the building height, and the wind speed at the weather station. Infiltration caused by the inside-outside temperature difference depends upon the perimeter of the building, a flow coefficient (same as above), the atmospheric pressure, the height of the neutral pressure level above the ground, and the inside-outside temperature difference. Some of the papers describing the high-rise building algorithm are included in Appendix B.

Infiltration in low-rise apartment buildings is the topic of a recent paper by Hunt, Porterfield, and Ondris (1977). This work, done in Chicago (USA), compares infiltration measured using SF_6 tracer gas with air leakage determinations made using a fan-pressurization technique. The results show significant differences in leakage measurements for apartments which are not reflected in corresponding infiltration data. Projections of pressure differences required to produce observed infiltration rates are much lower than those which were actually present during the measurements. Clearly, this complex problem merits further examination.

The National Bureau of Standards (USA) has described an infiltration algorithm based upon a model developed by Sander and Tamura (1973). This approach is described in Appendix B. Researchers at the Construction Engineering Research Laboratory (USA) have decided to extend the residential-based models to commercial buildings by adopting the formulae: $INF = INF\ (Design) \cdot SCHEDULE \cdot (A + B \cdot \Delta T + C \cdot W) \cdot \rho$. Infiltration rate at design conditions is a required input. SCHEDULE is either 1 or 0 depending on whether the building is pressurized at the time ΔT and W are measured.

User Influences

Variations in personal behavior cause a significant difference in infiltration rates in buildings. At present there is no theoretical model for predicting confidently the amount of infiltration within a building, as the numerous significant variables are both physical and behavioral and are difficult to measure and predict (Harrje and Grot, 1977). As Sonderegger has shown (1977), this is a problem that pervades energy conservation modeling in general. Princeton University studies of similar townhouses in Twin Rivers, N. J. (USA), has shown that 46 percent of the variation in energy usage for residential space heating could only be explained by occupant behavior, not by structural differences.

Two things are apparent about behavioral variables: (1) people influence air infiltration rates directly by opening and closing windows and doors, by using ventilating fans, and through furnace operation and (2) they influence rates indirectly through a complex interaction of living habits. Stricker (1975) used comprehensive questionnaires to determine "living habits" (including occupancy patterns and tobacco consumption) before measuring leakage rates of houses. However, little information exists concerning these indirect psychological aspects. Extensive work has been done, on the other hand, to determine the parameters that directly influence occupants to modify air infiltration rates of their homes.

In a British study, Dick and Thomas (1951) recorded window positions and vent openings in 15 houses over a period of 26 weeks. They found that the outside temperature alone accounted for 70 percent of the window openings, and that 10 percent of the variance could be attributed to wind speed (although there was difficulty in determining the correlation of opening of windows due to effects of temperature and wind speed simultaneously).

Far more erratic behavior was observed by Baird (1969) in a study of air infiltration in hospital ward rooms. Here the frequency and duration of both window and door movement was recorded. Other infiltration tests were carried out in Minnesota (USA) and a record was kept of the number of times doors were opened and closed during three winters (Jordan, Erickson, and Leonard, 1963). A correlation was expected between opening the basement door and observed increases in stack effect but the data were inconclusive. Malik (1977) did observe significant effects on infiltration rates in townhouses when basement doors were opened and when window opening habits changed. Closing tightly and locking a window in winter reduced infiltration compared to loose closure during mild weather.

The traffic rate through mechanical and automatic opening doors in office buildings has been measured and correlated with air infiltration rates by Min (1958). An earlier study observed air infiltration through a window when it was closed, locked, weather-stripped, and sealed for a full range of wind speeds (Houghton and Schroder, 1924). Included in this study were measurements of the porosity of plaster walls when layers of paint were added. Single coats of paint brought about significant changes in air infiltration rates.

After windows and doors, the most important user-influenced parameter is furnace operation. In the Twin Rivers townhouse project considerable variation was noted in temperature preference (thermostat setting) among residents, with corresponding differences in furnace operation. Janssen, Torborg, and Bonne (1977) have reported several studies of seasonal furnace efficiency. Changes in infiltration rates because of furnace operation are important considerations in calculating seasonal efficiency. Furnace operation affects infiltration rates in two ways. The need for combustion air causes an increase in infiltration. On the other hand, the air flow up the flue during combustion decreases exfiltration. The combination of the two effects results in a net increase in infiltration; however, the average increase is only 70 percent of the expected infiltration value due to combustion requirements.

A third behavior variable is the use of ventilators and humidifiers. An Australian study determined the effect of ventilators required by the building codes in providing minimum air exchanger rates (Howard, 1966). The ventilators were found to be insignificant in modifying the atmosphere of occupied homes because their area was small relative to the total area of the crackage around the windows. In experiments on the operation of the shower fan, clothes dryer, and range fan together, a striking increase in infiltration rates was recorded (Jordan, Erickson , and Leonard, 1963). In a Canadian study, smoking was found to increase demand for ventilation (Stricker, 1975). In the same study, humidity level effects were examined; the addition of moisture into the living space swelled the wood in window frames and sealed or reduced the size of the cracks, thus reducing air infiltration.

3.0 PROPOSED RESEARCH AGENDA

The literature survey reveals an abundance of research conducted over the past 30 years in the field of air infiltration in buildings, and an extensive list of applied research projects can be generated.

A telephone survey of some of the IEA representatives was conducted in order to determine specific areas of interest in infiltration research. Most participants desired a validated algorithm for computer programs which presently analyze building energy consumption in 1-hour steps for a 1-year period. Because these computer programs are usually applied to designs of new large buildings, an adequate algorithm for large buildings is of highest priority.

All participants also expressed interest in an algorithm or improved design data for small residential building infiltration loads. As can be seen in the summary of the literature survey, most of the past infiltration research has been in this area. Also, as previously noted, little success has been achieved to date in establishing a mathematical model which is adequately based upon the physical parameters of a small structure. Based upon the participants' expressed interests, the authors have considered separately these two main issues: (1) the need for a validated algorithm which is of adequate accuracy (relative to other calculation procedures) to be incorporated easily into the logic structure of existing hour-by-hour computer simulations; and (2) the need for applied research to understand the physics of air infiltration (the dynamic effects and the local boundary layer, physical phenomena in particular).

Members of the IEA also expressed an interest in determining in infiltration through open windows. This subject is presented later in this section.

Modeling Air Infiltration in Commercial Buildings

A few physical models have been developed for commercial buildings; the recent one developed by Tamura and Shaw appears to be the most advanced and deserves further consideration. The Tamura-Shaw algorithm described in Appendix B has been applied to eight multi-story buildings in Canada whose commonality includes age (all built in the sixties and early seventies), envelope architecture (rectangular geometry, curtain wall construction, fixed glazing), function (offices), and climatological location (Ottawa, Canada). The algorithm employs three basic equations which respectively account for the stack effect, the wind pressure effect, and a correlation (sub-additive summation) between these two driving potentials. The stack effect equation was developed based upon data obtained in field studies in the eight high-rise buildings. The wind equation is based upon data obtained from boundary layer wind tunnel tests with a 400:1 scale model. The data base has been established in both cases utilizing pressure measurements only. This experimental procedure yields only an approximate correlation to actual infiltration rates. The next step is to use tracer gas techniques to measure actual infiltration rates in a large building of simple geometry. State-of-the-art tracer-gas techniques demand the use of a large building site with a simple heating, ventilating, and air-conditioning (HVAC) system serving the entire structure in order to yeild direct, reliable results. Appendix E describes the United States field tests in two multi-story buildings using tracer gas. More tests should be performed over a much longer period of time, in a variety of temperature and wind conditions, with the HVAC system operating with 100 percent recirculated air and then with different increments in the amount of controlled outside air entry. In order to conduct these tests, it is necessary to:

(1) Survey and select building sites which have the following criteria:*

- Constant, rectangular, cross-sectional area
- Hi-rise (more than five stories)
- Office functions
- Single HVAC system (constant volume system with supply and return fans)
- Glass curtain wall construction
- Fixed glazing
- Recent construction
- Cold climate (to ensure substantial stack-driving potential).

(2) Install pressure taps, continuous flow tracer gas equipment, and a weather station, if possible. The pressure taps can be excluded if cost is excessive.*

(3) Design and conduct infiltration measurement procedures for the following cases, sequentially:*

- 100 percent air recirculation (polyethylene covers over the outside air dampers, relief air dampers, and toilet exhaust air outlets)
- Same as above, with exhaust air outlets open
- Minimum outside air entry (5-10 percent), toilet exhaust fans off, no pressurization of building

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* Research activities recommended for early implementation.

- Same as above, but exhaust air through toilet exhaust fan

- Pressurize building (through greater outside air entry) for a range of 0.1-1.0 inch of water across exterior walls, in increments of 0.1 inch of water.

The design of this step may be technically difficult and may require considerable planning. If the data analysis reveals reasonable validation of the Tamura-Shaw algorithm, the test procedure may be repeated to verify the algorithm for other building types and functions. The following sequence of experiments could be used:

- Same criteria as in (1) above, but the building should be multi-family residential (probably restricted to new construction)*

- Same criteria and building type, but the construction should be masonry, same criteria ~~and building type, but the operable~~

- Same criteria and building type, but the operable windows are closed,

- Same criteria, but the building should be low-rise multi-family, residential building, and, finally,

- Same criteria as above, but the operable windows are closed.

This process could be repeated for other simple geometries. This experimentation would adequately validate the Tamura-Shaw algorithm for a variety of buildings.

In addition to the tracer-gas experiments, air-leakage tests similar to those performed by the Canadians should be initiated to improve the data base on wall exposure air-leakage characteristics. These tests can be performed in actual buildings (preferably the same as those used for the tracer gas tests) and in a wind tunnel, as outlined by the papers in Appendix B.

Modeling Air Infiltration in Residential Structures

Despite the large number of studies which have been completed, significant questions about residential structures remain. Modeling the infiltration process have progressed from an approach using a statistical regression analysis (e.g., $INF = A + B \cdot W + C \cdot \Delta T$; where W and ΔT are the wind velocity and indoor-outdoor temperature difference, respectively; and A, B, and C are regression constants) to an approach which first considers appropriate physical models relating weather measurements to infiltration, then uses regression analysis to fit the physical model to measurements from a particular site. Any technique which uses a regression analysis demands a large data base which is obtained only through long-term measurements.

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* Research activities recommended for early implementation.

What is required is a procedure which will bypass the need for long-term infiltration measurements at a site. A technique is needed to measure the quantity that various authors call "building quality" of a house. This may be practical using a technique employed by Tamura (1975), Kronvall (1977), and others. A large fan or blower is mounted in a window or doorway of a house, and the speed of the fan is adjusted to produce a standard pressure difference across the walls of the house. The resulting air flow rate through the fan is the leakage rate through openings in the shell of the structure. Kronvall (1977) presents results of air leakage measurements in 13 houses. He suggests that an appropriate unit for air leakage standards is the unit of volume flow rate of leakage air (m^3/h) divided by the surface area of the house (m^2), measured at an arbitrary pressure difference of 50 Pa across the building envelope. It may be that the air leakage rate measured in this fashion can be quantitatively identified with the building quality of the house.

A problem arises at this point. Pressurization imposes a rather uniform pressure gradient on the walls of the house. Natural infilrat-tion is driven by wind and indoor-outdoor temperature differences which do not impose uniform pressure gradients on the building shell. There-fore, we are left with the interesting possibility that pressurization measurements may determine a "building quality" parameter which does not accurately assess the leakage of the flow paths actually used by natural infiltration. Comparisons must be made among leakage measurements using pressurization, infiltration measurements using a tracer gas, and the weather variables that drive the infiltration process.

Additional uncertainties must be examined before models of infiltra-tion in residences can be used with confidence. Infiltration modeling relies on weather data from a local weather station, and infiltration is driven by the microclimate conditions in the boundary layers of a house. These are not the same conditions. Can the microclimate be predicted if one knows the weather station conditions? Can the microclimate be predicted if both the weather station conditions are known and if simple on-site measurements similar in complexity to pressurization measurements can be made?

Finally, the modeler must deal with the effects of building occupancy. Building occupants, be they owners or tenants, change the building properties and therefore the infiltration. Therefore, adequate modeling must also consider average occupant behavior. Little is known about behavior causing changes in building properties.

The research agenda needed for improved models of infiltration in residences seeks to achieve several objectives:

- Develop a better way to determine building quality
- Improve our understanding of the relationship between local climate and a structure's microclimate
- Examine the effect of a building's occupant on the infiltration of that structure.

To these ends, specific projects can be suggested:

Pressurization/infiltration correlations. Measurements in individual houses of the leakage characteristics using pressurization/evacuation techniques, followed by tracer gas measurements of air infiltration rates, should be performed. A direct correlation between the two parameters could result from the investigation. It may also be possible that improved information for determining the equivalent crack length of a structure may result from the pressurization tests. Sites should include new structures; older, leaky structures; and newly retrofitted structures.*

Multi-chamber tracer gas measurements. Additional multi-chamber tracer-gas measurements are needed. Development and use of the tracer-gas measurement instrumentation will yield information about air exchange with the outdoors for different portions of a residence. The results of this investigation will provide valuable information about the stack effect and, in conjunction with boundary layer pressure measurements, will yield insight into exterior shielding effects. The effect of open interior doors on infiltration rates will also be determined.

Boundary layer (microclimate) investigations. Pressure measurements along the surface of real structures should be performed to yield valuable information indicating the accuracy of wind tunnel tests, as well as data on exterior shielding effects and dynamic responses to variable wind velocities.

Determining Infiltration Through Open Windows

Members of the IEA have expressed considerable interest in the effects on air infiltration of open windows in commercial and residential establishments. Expressed interest and prior research can be divided into three categories:

- Occupant motivation for opening windows
- Measurement of the amount of air infiltration through open windows
- Mathematical models to predict reliably the infiltration rate through an open window and the expected window opening behavior of occupants.

Dick and Thomas (Great Britain) and Brundrett (Great Britain) carried out investigations to correlate outdoor air temperatures and the frequency of the opening of windows in residences in the winter. As is expected, direct proportionality was found: lower temperatures resulted in a low frequency of window openings and high temperatures resulted in more openings.

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* Research activities recommended for early implementation.

Brundrett has also suggested the latter case holds true because the occupant is motivated to open the window to reduce the indoor relative humidity. Adamson (Sweden) states, based on Swedish studies, that indoor temperatures are probably too high, even in winter, so that the occupant is motivated to seek cool incoming air. In the United States, the National Bureau of Standards has performed some investigations in determining the frequency of window openings through observations of an office building. Adamson suggests that studies be conducted to determine the dependence of total ventilation (both passive and mechanical) on indoor temperature, indoor relative humidity, indoor activities (cooking, smoking, etc.) and outdoor temperatures. Other factors should be added to this list, particularly those representing constraints: outside ambient noise levels, outside ambient pollution levels, and rainfall.

In any case, it is evident that a data base needs to be developed to predict the probability of the number of window openings at any time. We recommend that the work of Brundrett and Adamson be supported further and be repeated in a variety of climates.* Until window openings can be predicted, the accuracy of infiltration algorithms to predict air change volumes will be inadequate.

Some attempts have been made to quantify the amount of air infiltration through open windows. Bergetzi, Hartmann, et al obtained the following average values for casement windows:

closed windows	0.15 air changes per hour
1 window, open 100 mm	2.5 air changes per hour
1 window, open 45°	6.0 air changes per hour
1 window, completely open	7.5 air changes per hour

Because no modeling techniques adequately handle air infiltration rate prediction for open windows, it is vital that a much larger data base be established for buildings other than residential structures. In particular, commercial buildings which are usually slightly pressurized by the HVAC system need to be investigated for those periods when the wind velocity pressure overcomes the exfiltration imposed by the HVAC system pressurization and when buildings are unpressurized.*

Few mathematical models have even considered open windows. Hartmann (Switzerland) has a "Z" factor, a coefficient multiplier to increase the infiltration rate predicted by the traditional ($A + B\Delta T + CW$) model, used primarily for residential applications. Tamura has stated

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* Research activities recommended for early implementation.

that the Tamura-Shaw algorithm is capable of handling one opening per wall exposure.*

The literature survey shows that physically-based models for multiple window openings in buildings are a long way off. In the near future, predictions, as far as computer simulations are concerned, may be addressed by increasing the data base previously mentioned and through the development of good "average" values for different weather conditions.**

Improving Measurement Techniques

In order to examine the entire infiltration question, a brief treatise of measurement procedures is required. Hitchen and Wilson (1967) present an excellent review of air infiltration measurement techniques reported in the literature through 1966. Advantages and disadvantages of various techniques and computational traps to avoid when analyzing data are discussed. In most residential applications, tracer-gas techniques are utilized to determine directly air infiltration rates. These techniques include rate-of-decay method, equilibrium concentration methods, transfer index method, and the steady concentration method (also referred to as continuous flow method). These techniques are generally limited to relatively small structures due to the requirements for uniform concentration of tracer gas within the structure, and they yield reliable estimates of infiltration rate at a minimum time step of 10-15 minutes. Even with these constraints, tracer gas techniques provide a viable mechanism to understand how air flows within a building structure.

Two other important problems are of current research interest in the field of measurement methods: the problems associated with multi-room buildings where different flow rates occur between different rooms; and the question of intercomparison tests between several tracer gases.

Dick (1950a) considers the problem of measuring the flow of tracer gas into another chamber (room) when the source and detector are in the same room. Baird (1969) treats the problem of multi-chamber ventilation rates in the context of his measurements of natural ventilation in hospital ward units. In this report, N_2O is used as the tracer gas in

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* The effect of open windows on the Tamura-Shaw algorithm is to increase the equivalent wall orifice area, which reduces the value of the thermal draft coefficient, α . (The building acts more like a stack of single-story structures.) The flow coefficient, CW, will be increased substantially, more than overcoming the reduced stack effect, and will predict the expected trend, that is, increased infiltration rate.

** It is crucial when developing the data base to establish the external shielding effects of surrounding structures. Variances of 500 to 600 percent have been established for shielded vs. unshielded structures.

a continuous flow procedure. To observe transfer between adjoining rooms, he measures the steady-state concentrations in each room. Honma (1975) developed an iterative procedure to calculate air flows between rooms in two tall blocks of flats in Sweden. His procedure allows calculation of total ventilation between rooms; of ventilation due to both supply and exhaust fans; and of ventilation due to infiltration through structural cracks and cracks around doors and windows. Known amounts of a tracer gas (CO_2) are injected into selected rooms in the flats; measurements of changes in concentration of tracer as a function of time allow calculation of air flows. The ability to map air flow horizontally and vertically within a structure would add substantially to the knowledge of physical phenomena related to infiltration, as well as contribute to the validation of an infiltration algorithm. To this end, it is suggested that two specific research and development projects be conducted:

- Multi-chamber continuous flow air infiltration instrumentation should be developed. The rate of change (addition) of tracer gas in each of several chambers of an individual structure will provide new knowledge of air exchange with the outdoors for multiple chambers simultaneously. Sinden (1976a) presents a theoretical model for multichamber measurements and considers how one might obtain values for inter-chamber flow rates. In addition he examines the operational advantages of continuous flow measurement techniques.

- The feasibility of multiple tracer-gas usage should be studied. One gas for each of several chambers serves the same purpose as stated above as well as determining specific patterns of air flow within and through the structure. Technical problems related to sedimentation and mixing as well as the expected high cost of instrumentation may be prohibitive for a field demonstration.

Comparison measurements of infiltration rates using different trace gases have been reported by Howard (1966) and by Hunt and Burch (1975). Howard compared N_2O and H_2; and N_2O and O_2. N_2O and O_2 gave similar results; H_2 gave significantly large infiltration values than N_2O.

Hunt and Burch made comparisons between SF_6 and He. Differences in infiltration rates of about 18 percent were seen; the differences were not systematic. In the U.S., a standard test procedure for tracer-gas techniques is being developed by American Society for Testing and Materials. One criteria of the standard is the selection of the actual tracer gas. A multi-gas comparison for a determination of air infiltration rates in a simple structure should be conducted. Installation of equipment to disperse and measure three or four tracer gases (N_2O, CH_4, SF_6, and CO_2 are likely candidates) should be performed to see if the infiltration rate is the same.

One final measurement problem exists and may be difficult to solve. As previously stated, it is highly desirable to measure actual air infiltration rates in large buildings through the use of a tracer gas. Technical problems in mixing (for uniform concentration), settling, and dispersing large amounts of gas may occur. These problems must be addressed before the actual tests suggested to verify the Tamura-Shaw algorithm can be initiated.

Kelnhofer, Hunt, and Didion (1976) have reported measurements of infiltration into a nine-story office building using an SF_6 tracer gas technique. They investigated a building in which all floors were sealed except the ground floor and the mechnical equipment room at the top of the building. A central air distribution system allowed whole-building injection via the air supply system and whole-building sampling using the return air ducts. To verify their infiltration results a second independent calculation was performed which involved direct measurement of ventilation air-flow rates. Their paper is included in Appendix E. Hunt (1977) also has performed SF_6 experiments for a one-week period in a seven-story building, and attempts were made to quantify a stack effect through injection of SF_6 on the lower three floors only. The results were inconclusive, possibly due to a lack of detailed information about exhaust conditions during the data collection period. The two U.S. field tests used the rate-of-decay method. It is preferable to use the automated, continuous flow method to gather more hours of data with greater ease.

Centralized Data Management Center

In addition to these research activities, it is recommended that a high priority be given to the establishment of a centralized data repository for air infiltration data. Four primary functions which the Center could undertake are:

1. Catalog and transfer information. Published and unpublished papers, as well as unprocessed data from infiltration studies, will be available at a single location. In addition, the center will provide bibliographic services and reproductions of documents or computer tapes on request and translate important works into English at the request of IEA participants. Finally, the center will publish the results of infiltration research undertaken by the participants. The data management center will provide these services to all IEA participants, and possibly to non-participants engaged in serious research on air infiltration.

2. Standardize procedures for reporting experimental results. Standardized formats will be prepared for reporting the results of air-infiltration research. Particular emphasis will be placed on documenting test-building characteristics and data-collection procedures (e.g., number of hours, instrumentation, gas used, calibration techniques).

3. Collect additional information on completed test from researchers. The center will collect additional documentation and test data (e.g., copies of computerized data bases, photographs) from previous air-infiltration tests. This information will permit the use of a larger data base to validate air-infiltration models developed on limited test data.

4. Calibrate and validate air-infiltration models using existing data. The center will use available, high-quality air-infiltration test data to calibrate and validate infiltration models that are of special interest to the participants. The center will recalculate coefficients for infiltration models as needed and compare the ability of alternative models to represent air infiltration accurately and efficiently. The results of such comparisons will be made available to all participants.

Summary

An extensive list of infiltration research projects have been suggested but the list should be narrowed by IEA members. A chart on the next page tentatively lists those projects which appear to have either high interest by IEA members or near-term return.

For immediate consideration by the IEA, the following projects are proposed:

- Establishment of a centralized data management center
- Design and conduct of tracer gas measurement in a large commercial building; model infiltration for the building using the Tamura-Shaw algorithm and others that may be of interest
- Measurements to correlate pressurization leakage ratio with infiltration in selected residences
- Open window infiltration measurements and determination of occupant motivation for opening of windows.

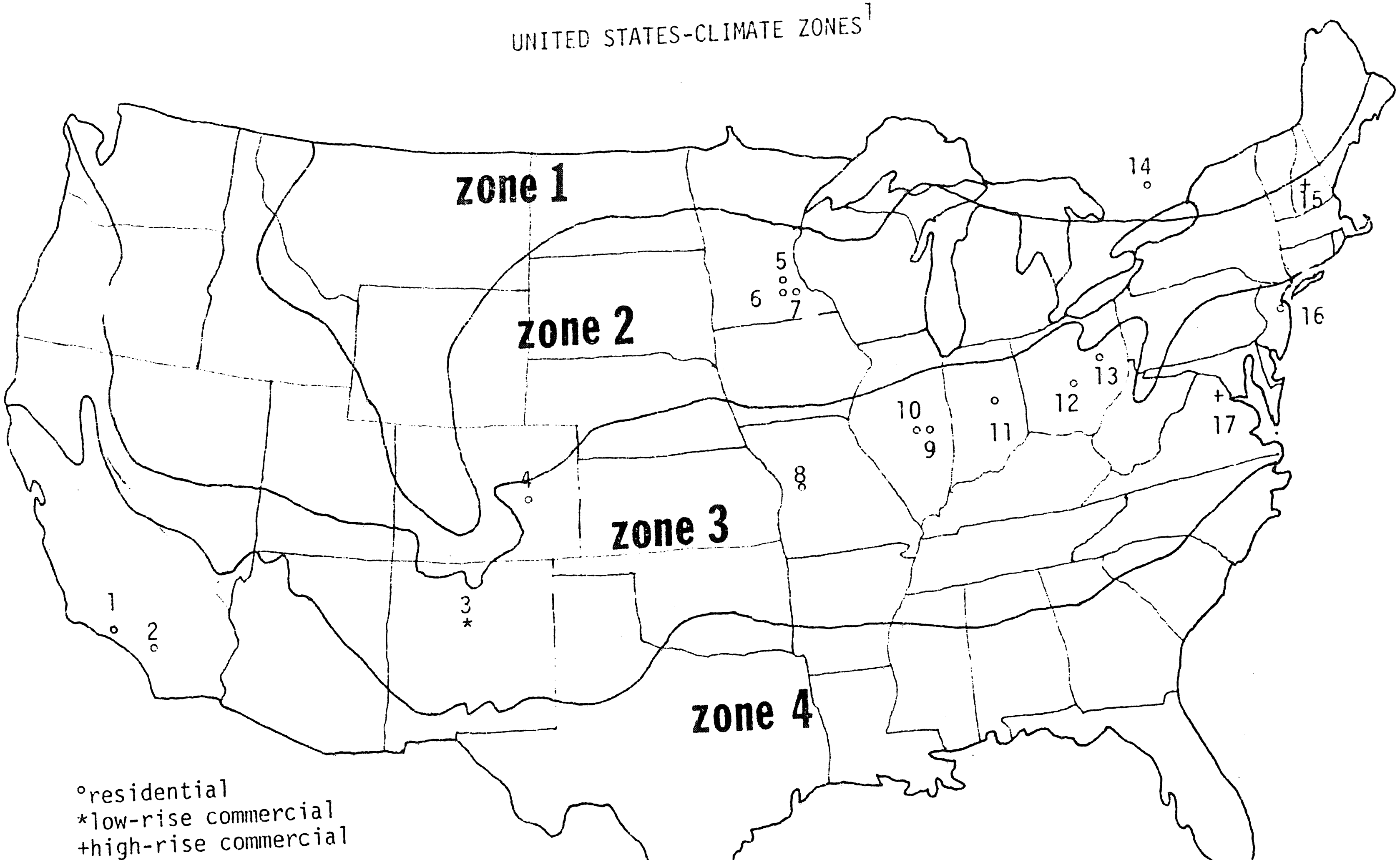
Project	Importance* (5-high) (1- low)	Time of Results** (5-fast) (1-slow)
• **Commercial Building Algorithm Validation**		
1. High-rise offices	4	4
2. High-rise multi-family	5	3
3. Masonry construction	5	2
4. Same as 2, operable windows	4	2
5. Low-rise multi-family	4	2
6. Same as ~~4~~ 5, operable windows	5	2
• **Open Windows**		
1. Motivation experiments	5	3
2. Measurement of infiltration	5	4
3. Modeling	4	1
• **Measurement Methodology**		
1. Multi-chamber tracer	4	4
2. Multiple gas usage	2	1
3. Gas Comparison	3	5
• **Centralized Data Management Center**	5	4
• **Residential Building**		
1. Pressurization/Infiltration Correlation	5	5
2. Micro-climate evaluation	3	1
3. Multi-chamber tracer-gas tests	3	2

* Based on the authors' own opinion and upon limited informal written and telephone communications with IEA participants.

** A project rated 5 could probably return significant results within 1 year. A project rate 1 might take 5 or more years for completion.

FIGURE 1. INFILTRATION TEST SITES

UNITED STATES-CLIMATE ZONES[1]



[1] BASED ON HEATING DEGREE DAYS

APPENDIX A

ANNOTATED BIBLIOGRAPHY

A REVIEW ARTICLE EXAMINING ONE OF THE FUNCTIONS OF INFILTRATION, MAINTAINING INDOOR AIR QUALITY.
ASHRAE TRANS. 1971, 77Ξ 50-60

1.0.5
"A REVIEW OF THE LITERATURE ON THE STRUCTURE OF WIND "TURBULENCE, WITH SPECIAL REGARD TO ITS EFFECT ON BUILDINGS "
-JONES (1968)
AVAILABLE METHODS OF INVESTIGATING WIND STRUCTURE IN THE FIELD ARE REVIEWED, AND COMMENTS ARE MADE ON THE NEED TO STUDY CONDITIONS IN URBAN AREAS.
BUILD. SCI. 1968; 3Ξ 41-50

2.0 INSTRUMENTATION TECHNIQUES

2.1 TRACER GAS

2.1.1
"MEASUREMENT OF INFILTRATION IN TWO RESIDENCES" PART ONE
-BAHNFLETH, MOSELEY, HARRIS (1957)
CORRELATES INFILTRATION RATES WITH WIND VELOCITY AND DIRECTION USING HELIUM AS TRACER GAS, MEASURED WITH A KATHAROMETER.
ASHRAE TRANS. 1957; 63Ξ 439-452

2.1.2
"AIR CHANGE AND AIR TRANSFER IN A HOSPITAL WARD UNIT"
-BAIRD (1969)
INFILTRATION RATES MEASURED USING NITROUS OXIDE UNDER VARYING VENTILATING CONDITIONS IN HOSPITAL ROOMS.
BUILD. SCI. 1969; 3Ξ 113-123

2.1.3
"MESSUNG DES NATURLICHEN LUFTWECHSELS IN NICHTKLIMATISIERTEN "WOHNRAUMEN "
-BARGETZI, HARTMANN, PFIFFNER (1977) GERMAN
EXAMINES THE EFFECT OF OCCUPANCY HABITS ON THE INFILTRATION RATE INTO A STRUCTURE, USING NITROUS OXIDE AS THE TRACER GAS.
SCHWEIZ. BAUZTG. 1977; 95Ξ HEFT 14Ξ 3-7

2.1.4
"DESIGN AND PERFORMANCE OF A PORTABLE INFILTRATION METER"
-COBLENTZ, ACHENBACH (1957)
A DESCRIPTION OF THE DEVELOPMENT OF THE NBS HELIUM TRACER SYSTEM WHICH WAS USED IN MOST SUBSEQUENT WORK IN THIS FIELD UNTIL THE INTRODUCTION OF SULFUR HEXAFLUORIDE INSTRUMENTATION.
ASHRAE TRANS. 1957; 63Ξ 477-482

2.1.5
"MEASUREMENT OF VENTILATION RATES USING A RADIOACTIVE TRACER"
-COLLINS, SMITH (1955)
USE OF RADIOACTVE ARGON TO MEASURE VENTILATION, WITH RESULTS SUCCESSFULLY CORRELATED TO HELIUM TRACER MEASUREMENTS.
J.INST.HEAT.VENT.ENG. 1949; 17Ξ 420-455

2.1.6
"MEASUREMENTS OF VENTILATION USING TRACER GAS TECHNIQUES"
-DICK (1950)
DISCUSSES TRACER GAS TECHNIQUES, USING HYDROGEN OR HELIUM WITH A KATHAROMETER AS A DETECTOR. ONE OF FOUR GERMINAL

PAPERS PUBLISHED BY DICK BETWEEN 1949 AND 1951.
HEAT.PIPING AIR COND. 1950; 22: 131-137

2.1.7
"AIR CHANGE MEASUREMENTS USING A TRACER GAS TECHNIQUE"
-DOEFFINGER (1976)
SULFUR HEXAFLOURIDE USED TO MEASURE THE INFILTRATION RATE
INTO A ONE-STORY OFFICE BUILDING.
PENN.STATE U. REPORT-DEPT. OF ARCH.ENG. MARCH 1976

2.1.8
"EXPERIMENTAL CHARACTERIZATION OF VENTILATION SYSTEMS
"IN BUILDINGS "
-DRIVAS, SIMMONDS, SHAIR (1972)
THE TECHNOLOGY OF OUTDOOR AIR POLLUTION APPLIED TO INDOOR
AIR QUALITY. STUDY OF VENTILATION EXHAUST-REENTRY PROBLEMS
USING SULFUR HEXAFLOURIDE AS A TRACER GAS.
ENVIRON. SCI. TECHNOL. 1972; 6: 609-614

2.1.9
"NATURAL VENTILATION OF MODERN TIGHTLY CONSTRUCTED HOUSES"
-ELKINS, WENSMAN (1971)
DESCRIBES THE USE OF ETHANE TO MEASURE INFILTRATION RATES
IN TWO OCCUPIED HOUSES.
AGA CONFERENCE ON NATURAL GAS RESEARCH AND TECHNOLOGY,CHICAGO 2/28-3/3, 1971

2.1.10
"USE OF GAS AND PARTICLE TRACERS IN THE STUDY OF INFECTION
"TRANSMISSION"
-FOORD (1973)
FREON 12, FREON 114, AND B.C.F. USED WITH ELECTRON CAPTURE DETECTOR
FOLLOWING GAS CHROMATOGRAPH, USING CONTINUOUS FLOW TECHNIQUE.
INVESTIGATED RELATIONSHIP BETWEEN PARTICLE MIGRATION AND AIR FLOW.
PROCEEDINGS OF FOURTH INTERNATIONAL SYMPOSIUM ON AEROBIOLOGY
HELD AT TECHNICAL UNIVERSITY AT ENSCHEDE, THE NETHERLANDS
OOSTHOEK PUB. CO. UTRECHT 1973 450-454
ED. J.F. PH. HERS & K.C. WINKLER

2.1.11
"DIE TECHNIK DER LUFTWECHSELBESTIMMUNG MIT RADIOAKTIV KRYPTON-85
"UND IHRE ANWENDUNG AUF UNTERSUCHUNGEN IN STALLEN"
-GOTTLING, DOMBERG, HILLEGER, VOGG (1972) GERMAN
RADIOACTIVE TRACER GAS USED TO MEASURE AIR INFILTRATION
IN A STABLE.
GESUND. ING. 1972; 93: 15-20

2.1.12
"BACTERIAL CONTAMINATION IN A MODERN OPERATING SUITE. PART ONE:
"EFFECT OF VENTILATION ON AIRBORNE PARTICLES"
-HAMBERAEUS, BENGTSSON, LAURELL (1977)
NITROUS OXIDE USED AS A TRACER GAS AND POTASSIUM IODIDE AS A
PARTICULATE TO TRACE AIR MOVEMENTS WITH HIGH VENTILATION
RATES PRESENT.
J. HYG. CAMB. 1977; 79: 121-132

2.1.13
"AUTOMATED AIR INFILTRATION MEASUREMENTS AND IMPLICATIONS
"FOR ENERGY CONSERVATION"
-HARRJE, GROT (1977)
DESCRIBES AUTOMATED SULFUR HEXAFLOURIDE INFILTRATION SYSTEM.
PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON ENERGY USE MANAGEMENT

(TUCSON, AZ, OCT. 1977) NEW YORK; PERGAMON 457-464

2.1.14
"DYNAMIC CHARACTERISTICS OF AIR INFILTRATION"
-HILL, KUSUDA (1975)
CARBON DIOXIDE USED AS A TRACER GAS TO EVALUATE EXPERIMENTALLY
THE EFFECT OF FLUCTUATING WIND SPEEDS AND PRESSURE DIFFERENCES
ACROSS THE ENCLOSURE ON INFILTRATION.
ASHRAE TRANS. 1975; 81= 168-185

2.1.15
"VENTILATION OF BUILDINGS AND ITS DISTURBANCES"
-HONMA (1975)
DESCRIPTION OF AIR FLOW MEASUREMENTS IN APARTMENTS
IN TWO HIGH-RISE BUILDINGS.
FAIBO GRAFISKA, STOCKHOLM (1975)

2.1.16
"VENTILATION MEASUREMENTS IN HOUSES AND THE INFLUENCE OF
"WALL VENTILATORS"
-HOWARD (1966)
USES NITROUS OXIDE AS A TRACER GAS TO STUDY WIND EFFECTS ON
INFILTRATION RATES IN SUBURBAN HOUSES.
BUILD. SCI. 1966; 1= 251-257

2.1.17
"MEASUREMENTS OF AIR MOVEMENTS IN A HOUSE USING A
"RADIOACTIVE TRACER GAS"
-HOWLAND, KIMBER, LITTLEJOHN (1960)
EXPERIMENTS USING RADIOACTIVE KRYPTON TO MEASURE AIR
MOVEMENTS IN A TYPICAL SUBURBAN HOUSE.
J.INST.HEAT.VENT.ENG. 1960; 28= 57-71

2.1.18
"AIR EXCHANGE AND VENTILATION SYSTEM MEASUREMENTS IN THE
"NORRIS COTTON FEDERAL OFFICE BUILDING IN MANCHESTER
"NEW HAMPSHIRE"
-HUNT (1977)
AIR EXCHANGE RATES WERE MEASURED USING SULFUR HEXAFLOURIDE
IN AN ENERGY-SAVING DESIGNED OFFICE BUILDING.
REPORT OF TEST TO ERDA 1977;

2.1.19
"AIR INFILTRATION MEASUREMENTS IN A FOUR-BEDROOM TOWNHOUSE
"USING SULFUR HEXAFLOURIDE AS A TRACER GAS"
-HUNT, BURCH (1975)
A CONTROLLED EXPERIMENT IN WHICH WIND EFFECTS ARE COMPLETELY
ELIMINATED. PROBLEMS IN SAMPLING AND MIXING THE GAS WERE
INVESTIGATED, AND POTENTIAL SOURCES OF ERROR IN TRACER GAS
MEASUREMENTS WERE CONSIDERED.
ASHRAE TRANS. 1975; 81= 186-201

2.1.20
"INFILTRATION IN RESIDENTIAL HOUSES"
-JANSSEN, GLATZEL, TORBORG, BONNE (1977)
METHANE USED AS A TRACER GAS TO MEASURE AIR INFILTRATION
IN HOMES OF THREE DIFFERENT CLIMATIC REGIONS.
ASME SYMPOSIUM PROCEEDINGS, ATLANTA, GA., NOV. 1977

2.1.21
"DETERMINATION OF COMBINED AIR EXFILTRATION AND VENTILATION
"RATES IN A NINE-STORY OFFICE BUILDING"

-KELNHOFER, HUNT, DIDION (1976)
USE OF SULFUR HEXAFLOURIDE AS A TRACER GAS IN AN OFFICE BUILDING WITH SEALED WINDOWS THROUGHOUT. THE MAIN TRUNK OF THE AIR SUPPLY WAS USED FOR INJECTION, WITH SAMPLING AT THE RETURN AIR LINE.
PROCEEDINGS OF CONFERENCE ON IMPROVING EFFICIENCY AND PERFORMANCE OF HVAC EQUIPMENT AND SYSTEMS FOR COMMERCIAL AND INDUSTRIAL BUILDINGS PURDUE UNIV., APRIL 12-14, (1976) 322-328

2.1.22
"THE EVALUATION OF VENTILATION"
-LIDWELL (1960)
A DISCUSSION ON THE USE OF NITROUS OXIDE AND ACETONE VAPOR AS TRACER GASES TO STUDY VENTILATION.
J.HYG. 1960; 58: 297-305

2.1.23
"ELECTRON ABSORPTION DETECTORS AND TECHNIQUE FOR USE IN "QUANTITATIVE AND QUALITATIVE ANALYSIS BY GAS CHROMOTOGRAPHY"
-LOVELOCK (1963)
DESCRIBES THE BASIS OF OPERATION OF ELECTRON ABSORPTION DETECTORS FOR SULFUR HEXAFLOURIDE AS A TRACER GAS.
ANAL. CHEM. 1963; 35: 474-481

2.1.24
"UEBER DEN LUFTWECHSEL IN WOHNGEBAUDEN"
-PETTENKOFER (1858)
MEASURED VENTILATION IN ROOMS USING CARBON DIOXIDE PRODUCED BY BURNING CHARCOL AS THE TRACER GAS. CONCENTRATION DETERMINED BY ABSORBING THE GAS IN LIME WATER.
MUNICH, 1858

2.1.25
"THE VARIATION OF INFILTRATION RATE WITH RELATIVE "HUMIDITY IN A FRAME BUILDING"
-LUCK, NELSON (1977)
USE OF CHLOROTHENE GAS TO MEASURE INFILTRATION RATE, WITH THE RESULTS CORRELATED TO INSIDE RELATIVE HUMIDITY.
ASHRAE TRANS. 1977; 83-I:

2.1.26
"OSU/EPRI FINAL REPORT--CHAPTER 9, AIR INFILTRATION"
-SEPSY, JONES, MCBRIDE, BLANCETT (1977)
MEASUREMENTS MADE USING AUTOMATED SULFUR HEXAFLOURIDE TRACER GAS SYSTEM DEVELOPED BY NES/PRINCETON.
OSU/EPRI FINAL REPORT 1977; ENVIRONMENTAL CONTROL GROUP DEPT. OF MECHANICAL ENGINEERING, COLUMBUS, OHIO 43210

2.1.27
"THEORETICAL BASIS FOR TRACER GAS MEASUREMENTS OF "AIR INFILTRATION"
-SINDEN (1976)
A THEORETICAL TREATMENT OF THE PROBLEM OF CONCENTRATION MEASUREMENTS IN A MULTI-CHAMBER STRUCTURE. DEVELOPS A TECHNIQUE FOR THE ANALYSIS OF STEADY-STATE CONCENTRATIONS IN THIS SITUATION.
PRINCETON UNIV; TWIN RIVERS PROJECT, NOTE 5, MARCH 1976

2.1.28
"CONTAMINANT DISPERSION AND DILUTION IN A VENTILATED SPACE"
-WEST (1977)

METHANE USED AS A TRACER GAS. GOOD MIXING OF GAS, ALTHOUGH CONCENTRATION SPIKES WERE OBSERVED.
ASHRAE TRANS. 1977; 83-I: 125-140

2.2 PRESSURIZATION

2.2.1
"STANDARD TEST METHOD FOR RATE OF AIR LEAKAGE THROUGH
"EXTERIOR WINDOWS, CURTAIN WALLS, AND DOORS"
-ANSI/ASTM (1976)
GIVES BASIC OUTLINE OF APPARATUS, PROCEDURE, AND CALCULATIONS FOR PRESSURIZATION TECHNIQUE.
ASTM STANDARD E283-73

2.2.2
"INFRASONIC IMPEDANCE MEASUREMENTS OF BUILDINGS FOR AIR
"LEAKAGE DETERMINATION"
-GRAHAM (1977) MASTER'S THESIS
AN INNOVATIVE TECHNIQUE USING INFRASONIC IMPEDANCE CHARACTERISTICS TO MEASURE THE AIR LEAKAGE PROPERTY OF A BUILDING. DESCRIBES THE DIAPHRAM-TYPE, MOTOR-DRIVEN SOURCE, AND THE PRESSURE SENSOR USED FOR MEASURING THE IMPEDANCE.
M.S. THESIS, SYRACUSE UNIV. 1977

2.2.3
"AIR LEAKAGE THROUGH THE OPENINGS IN BUILDINGS"
-HOUGHTEN, SCHRADER (1924)
BLOWER APPARATUS DESIGNED TO MEASURE AIR FLOW THOUGH EXPERIMENTAL WINDOWS BUILT IN A SECTION OF WALL.
ASHRAE TRANS. 1924; 30: 105-120

2.2.4
"AIR LEAKAGE MEASUREMENTS IN THREE APARTMENT HOUSES IN THE
"CHICAGO AREA"
-HUNT, PORTERFIELD, ONDRIS (1977)
FAN PRESSURIZATION USED TO DETERMINE AIR LEAKAGE IN LOW RISE APARTMENTS.
NATIONAL BUREAU OF STANDARDS REPORT 1977

2.2.5
"TESTING OF HOUSES FOR AIR-LEAKAGE USING A PRESSURE METHOD"
-KRONVALL (1977)
DESCRIBES AN INEXPENSIVE AND EASILY ADAPTABLE TECHNIQUE FOR MEASURING AIR LEAKAGE IN SWEDISH HOUSES. INCLUDES STUDIES OF AIR LEAKAGE DETECTED BY THERMOGRAPHY, AND THE NEW STANDARDS FOR AIR TIGHTNESS IN SWEDISH HOUSES.
LUND INSTITUTE OF TECHNOLOGY, DIV. OF BUILD. TECH. 1977;

2.2.6
"AIR LEAKAGE VALUES FOR RESIDENTIAL WINDOWS"
-SASAKI, WILSON (1965)
THIRTY NINE RESIDENTIAL WINDOWS WERE TESTED IN A PRESSURE CHAMBER FOR AIR LEAKAGE RATES.
ASHRAE TRANS. 1965; 71: 81-88

2.2.7
"AIR INFILTRATION THROUGH REVOLVING DOORS"
-SCHUTRUM, OZISIK, BAKER, HUMPHREYS (1961)
EXPERIMENTS CARRIED OUT UNDER HEATING AND COOLING CONDITIONS TO MEASURE AIR INFILTRATION IN BOTH MANUAL AND AUTOMATIC REVOLVING DOORS.
ASHRAE TRANS. 1961; 67: 488-506

2.2.8
"MEASUREMENT OF AIR-TIGHTNESS OF HOUSES"
-STRICKER (1975)
PRESSURIZATION TECHNIQUE USED TO DETERMINE LEAKAGE AREA OF A HOUSE. EXHAUST FAN INSTALLED IN WINDOW WITH MEASUREMENTS TAKEN OF PRESSURE DROP ACROSS FAN TO DETERMINE AIR FLOW.
ASHRAE TRANS. 1975; 81≡ 148-167

2.2.9
"MEASUREMENTS OF AIR LEAKAGE CHARACTERISTICS OF HOUSE "ENCLOSURES"
-TAMURA (1975)
PRESSURIZATION TECHNIQUE USED ON SIX HOUSES TO ESTABLISH OVERALL AIR LEAKAGE, AND COMPONENT LEAKAGE THROUGH WINDOWS, DOORS, WALLS, AND CEILINGS.
ASHRAE TRANS. 1975; 81≡ 202-211

2.3 WIND TUNNEL AND OTHER TECHNIQUES

2.3.1
"WIND PRESSURE ON BUILDINGS INCLUDING EFFECTS OF ADJACENT "BUILDINGS"
-BAILEY, VINCENT (1944)
THE RELATIONSHIP BETWEEN WIND SPEED AND THE DISTRIBUTION OF WIND PRESSURE OVER BUILDINGS IS DETERMINED THROUGH STUDYING MODELS IN A WIND TUNNEL.
J.INST.CIV.ENG. 1943; 20≡ 243-275

2.3.2
"MODEL VERIFICATION OF ANALOGUE INFILTRATION PREDICTIONS"
-BILSBORROW, FRICKE (1975)
SCALE MODEL BUILDINGS USED TO VERIFY NATURAL VENTILATION RATE CALCULATIONS BASED ON DIGITAL ANALOGUE STUDIES.
BUILD. SCI. 1975; 10≡ 217-230

2.3.3
"COMBINED THERMAL AND AIR LEAKAGE PERFORMANCES OF "DOUBLE WINDOWS"
-BURSEY, GREEN (1970)
MEASUREMENTS TAKEN OF AIR LEAKAGE RATES ACROSS WINDOWS IN A GUARDED HOT BOX CALORIMETER WITH A SYSTEM FOR CREATING A PRESSURE DIFFERENCE ACROSS THE WINDOW.
ASHRAE TRANS. 1970; 76≡ 215-226

2.3.4
"ADVENTITIOUS VENTILATION OF HOUSES"
-HARRIS-BASS, KAVARANA, LAWRENCE (1974)
A MODEL SCALE APPROACH TO NATURAL VENTILATION AIMED AT PREDICTING ROOM AIR MOVEMENTS AND VENTILATION RATES, COMPARED WITH FULL SCALE RESULTS AND THEORETICAL MODELS.
BUILD. SERV. ENG. 1974; 42≡ 106-111

2.3.5
"WIND AND TREES--AIR INFILTRATION EFFECTS ON ENERGY IN "HOUSING"
-MATTINGLY, PETERS (1975)
SMOKE AND WIND TUNNEL MODELING OF AIR FLOW OVER HOUSES, INCLUDING THE EFFECTS OF THE LOCAL TERRAIN.

PRINCETON UNIV. CENTER FOR ENVIRONMENTAL STUDIES, REPORT #20. MAY 1975

2.3.6 "
THE CALCULATION OF AIR INFILTRATION RATES CAUSED BY
WIND AND STACK ACTION FOR TALL BUILDINGS"
-SHAW, TAMURA (1977)
INFILTRATION RATES CAUSED BY WIND ACTION ALONE, AND IN
CONJUNCTION WITH STACK ACTION WERE MEASURED WITH PLEXIGLAS
MODELS IN A BOUNDARY LAYER WIND TUNNEL.
ASHRAE TRANS. 1977; 83-II

3.0 INVESTIGATION OF STRUCTURES

3.1 RESIDENCES

3.1.1
"MEASUREMENT OF INFILTRATION IN TWO RESIDENCES. PART ONE
"TECHNIQUE AND MEASURED INFILTRATION"
-BAHNFLETH, MOSELEY, HARRIS (1957)
INFILTRATION RATES MEASURED AND CORRELATED WITH WIND VELOCITY
AND DIRECTION, AND WITH INSIDE/OUTSIDE PRESSURE DIFFERENCES.
(2.1.1)

3.1.2
"MESSUNG DAS NATURLICHEN LUFTWECHSELS IN NICHTKLIMATISIERTEN
"WOHNRAUMEN"
-BARGETZI, HARTMANN, PFIFFNER (1977) GERMAN
EXAMINES OCCUPANCY EFFECTS ON INFILTRATION RATES.
(2.1.3)

3.1.3
"FIELD MEASUREMENTS OF AIR INFILTRATION IN TEN ELECTRICALLY
"HEATED HOUSES"
-COBLENTZ, ACHENBACH (1963)
AIR INFILTRATION RATES MEASURED TO ASSIST IN CORRELATING
COMPUTED HEATING LOADS WITH OBSERVED USE OF ELECTRICAL
ENERGY FOR HEATING. STUDY CARRIED OUT IN TEN TYPICAL ONE
AND TWO STORY BRICK AND FRAME HOUSES.
ASHRAE TRANS. 1963; 69= 358-365

3.1.4
"EXPERIMENTAL STUDIES IN NATURAL VENTILATION OF HOUSES"
-DICK (1949)
INFILTRATION CORRELATED TO WIND SPEED AND TEMPERATURE DIFFERENCES
IN FOUR SIMILAR HOUSES. MEASUREMENTS WERE MADE OF THE AIR FLOW
BETWEEN ROOMS AND THE AIR CHANGE IN ROOMS, OF THE HEAT LOST
BY VENTILATION, AND PRESSURE DISTRIBUTION ACROSS THE WALLS.
J.INST.HEAT.VENT.ENG. 1949; 17= 420-455

3.1.5 "
VENTILATION RESEARCH IN OCCUPIED HOUSES"
-DICK, THOMAS (1951)
CONTINUATION OF STUDIES IN NATURAL VENTILATION, LOOKING AT
SHELTERED AND EXPOSED SITES. INCLUDES DISCUSSION ON THE
WINDOW OPENING HABITS OF OCCUPANTS.
J.INST.HEAT.VENT.ENG. 1951; 19= 306-326

3.1.6

"NATURAL VENTILATION OF MODERN TIGHTLY CONSTRUCTED HOMES"
-ELKINS, WENSMAN (1971)
A YEAR-LONG STUDY OF INFILTRATION IN TWO OCCUPIED HOUSES IN OHIO.
(2.1.9)

3.1.7
"INFRASONIC IMPEDANCE MEASUREMENTS OF BUILDINGS FOR AIR "LEAKAGE DETERMINATION"
-GRAHAM (1975)
AN INSTRUMENTATION SYSTEM TO DETERMINE BUILDING IMPEDANCE IN ORDER TO FIND BUILDING AIR LEAKAGE PROPERTIES. SYSTEM MAY REQUIRE LESS TIME THAN BLOWER PRESSURIZATION, AND UNLIKE TRACER GAS TECHNIQUES, IS INDEPENDENT OF WEATHER CONDITIONS.
(2.2.2)

3.1.8
"RESIDENTIAL ENERGY CONSERVATION--THE TWIN RIVERS PROJECT"
-HARRJE, SOCOLOW, SONDEREGGER (1977)
TWENTY-NINE HOUSES INSTRUMENTED, WITH INTERNAL TEMPERATURES, APPLIANCE USEAGE, FURNACE OPERATION, THERMOSTAT SETTINGS, AND WINDOW AND DOOR USE MEASURED. UTILITY RECORDS WERE USED TO CORRELATE HOUSE SIZE, DESIGN, AND RETROFITS TO ENERGY CONSUMPTION. INCLUDES USE OF INFRARED SCANNING, AIR INFILTRATION MONITORING, AND WIND TUNNEL TESTS.
ASHRAE TRANS. 1977; 83(I)=

3.1.9
"VENTILATION MEASUREMENTS IN HOUSES AND THE INFLUENCE OF "WALL VENTILATORS"
-HOWARD (1966)
MEASUREMENTS OF VENTILATION RATES MADE IN SEVEN CLOSED ROOMS OF SIX HOUSES, USING NITROUS OXIDE AS THE TRACER GAS. HOUSES LOCATED IN OUTER SUBURBS OF MELBOURNE.
(2.1.16)

3.1.10
"MEASUREMENTS OF AIR MOVEMENTS IN A HOUSE USING A RADIOACTIVE "TRACER GAS"
-HOWLAND, KIMBER, LITTLEJOHN (1960)
AIR MOVEMENTS IN A TYPICAL SUBURBAN HOUSE MEASURED USING KRYPTON-85. EFFECT OF INTERIOR DOORS OPEN WITH WINDOWS SHUT INVESTIGATED.
(2.1.17)

3.1.11
"INFILTRATION IN RESIDENTIAL STRUCTURES"
-JANSSEN, GLATZEL, TORBORG, BONNE (1977)
METHANE USED AS A TRACER GAS TO MEASURE INFILTRATION IN HOMES IN MINNEAPOLIS, DENVER, AND KANSAS CITY, LOOKING AT THE EFFECTS OF THE THREE DIFFERENT CLIMATES.
(2.1.20)

3.1.12
"INFILTRATION MEASUREMENTS IN TWO RESEARCH HOUSES"
-JORDAN, ERICKSON, LEONARD (1963)
INVESTIGATIONS WERE MADE TO DETERMINE ENERGY REQUIREMENTS FOR RESIDENTIAL HEATING FOR TWO RESIDENCES IN MINNESOTA, WITH WIND AND TEMPERATURE DIFFERENCES RELATED TO AIR EXCHANGE.
ASHRAE TRANS. 1963; 69= 344-350

3.1.13

"TESTING OF HOUSES FOR AIR-LEAKAGE USING A PRESSURE METHOD"
-KRONVALL (1977)
DESCRIBES AN INEXPENSIVE AND EASILY ADAPTABLE TECHNIQUE FOR MEASURING AIR LEAKAGE IN SWEDISH HOUSES. INCLUDES STUDIES OF AIR LEAKAGE DETECTED BY THERMOGRAPHY, AND THE NEW STANDARDS FOR AIR TIGHTNESS IN SWEDISH HOUSES.
(2.2.5)

3.1.14
"STATISTICAL ANALYSES OF AIR LEAKAGE IN SPLIT-LEVEL RESIDENCES"
-LASCHOBER, HEALY (1964)
INFILTRATION RATES OF TWO HOUSS WERE MEASURED TO FURTHER DEFINE THEIR THERMAL CHARACTERISTICS. COLLECTED DATA WAS STATISTICALLY ANALYZED TO DETERMINE WHETHER INFILTRATION COULD BE RELATED TO WIND AND TEMPERATURE.
ASHRAE TRANS. 1964; 70E 364-374

3.1.15
"THE VARIATION OF INFILTRATION RATE WITH RELATIVE HUMIDITY "IN A FRAME BUILDING"
-LUCK, NELSON (1977)
ENERGY SAVING BENEFIT DETERMINED FROM INCREASING RELATIVE HUMIDITY DURING WINTER IN A MINNESOTA HOUSE. RELATIONSHIP OF INFILTRATION AND HUMIDITY OBSERVED.
(2.1.25)

3.1.16
"AIR INFILTRATION IN HOMES"
-MALIK (1977)
A M.S. THESIS CONTAINING DETAILED DESCRIPTION OF THE INFILTRATION MEASUREMENTS TAKEN IN THE PRINCETON TWIN RIVERS PROJECT.
PRINCETON UNIV. CENTER FOR ENVIRONMENTAL STUDIES REPORT 58, SEPT. 1977

3.1.17
"OSU/EPRI FINAL REPORT--CHAPTER 9, AIR INFILTRATION"
-SEPSY, JONES, MCBRIDE, BLANCETT (1977)
LARGEST SINGLE STUDY TO DATE ON AIR INFILTRATION IN RESIDENTIAL STRUCTURES.
(2.1.26)

3.1.18
"MEASUREMENT OF AIR-TIGHTNESS OF HOUSES"
-STRICKER (1975)
INFILTRATION RELATED TO HUMIDITY PROBLEMS STUDIED BY PRESSURIZATION TECHNIQUE IN CANADIAN HOUSES.
(2.2.8)

3.1.19
"AIR LEAKAGE AND PRESSURE MEASUREMENTS ON TWO OCCUPIED HOUSES"
-TAMURA, WILSON (1964)
MEASURED AIR LEAKAGE IS RELATED TO WEATHER CONDITIONS AND FURNACE OPERATION USING A TRACER GAS. MEASURED VALUES COMPARED TO THOSE OBTAINED BY ASHRAE PROCEDURE. INDOOR-OUTDOOR PRESSURE DIFFERENCES CORRELATED TO WIND VELOCITY AND DIRECTION.
ASHRAE TRANS. 1964; 70E 110-119

3.1.20
"MEASUREMENTS OF AIR LEAKAGE CHARACTERISTICS OF HOUSE "ENCLOSURES"
-TAMURA (1975)
PRESSURIZATION TECHNIQUE ON SIX WOOD-FRAME HOUSES TO ESTABLISH

OVERALL AIR LEAKAGE, AND COMPONENT LEAKAGE THROUGH WINDOWS, DOORS, WALLS, AND CEILINGS.
(2.2.9)

3.2 LOW RISE COMMERCIAL

3.2.1
"ENERGY CONSERVATION IN AN OLD THREE STORY APARTMENT COMPLEX"
-BEYEA, HARRJE, SINDEN (1977)
DESCRIBES SEVERAL WAYS TO MEASURE INFILTRATION IN A STRUCTURE. RESULTS APPLIED TO MEASUREMENTS IN APARTMENTS.
ENERGY USE MANAGEMENT, PERGAMON, NY 1977; II 373-383

3.2.2
"AIR CHANGE MEASUREMENTS USING A TRACER GAS TECHNIQUE"
-DOEFFINGER (1976)
TRACER GAS USED TO MEASURE AIR CHANGE RATES IN A SINGLE STORY OFFICE BUILDING. TESTS CONDUCTED WITH SUPPLY VENTILATION FAN BOTH ON AND OFF.
(2.1.7)

3.2.3
"EXPERIMENTAL CHARACTERIZATION OF VENTILATION SYSTEMS
"IN BUILDINGS"
-DRIVAS, SIMMONDS, SHAIR (1972)
TRACER EXPERIMENTS WITH SULFUR HEXAFLOURIDE WERE USED TO OBTAIN QUANTITATIVE DATA ON EXHAUST REENTRY IN BUILDINGS.
(2.1.8)

3.2.4
"AIR LEAKAGE MEASUREMENTS IN THREE APARTMENT HOUSES IN THE
"CHICAGO AREA"
-HUNT, PORTERFIELD, ONDRIS (1977)
MEASURED AIR LEAKAGE AND INFILTRATION IN INDIVIDUAL APARTMENTS.
(2.2.4)

3.3 HIGH RISE COMMERCIAL

3.3.1
"VENTILATION OF BUILDINGS AND ITS DISTURBANCES"
-HONMA (1975)
MEASUREMENTS OF TOTAL AIR FLOW IN FLATS IN HIGH-RISE APARTMENT BUILDINGS IN SWEDEN.
(2.1.15)

3.3.2
"AIR EXCHANGE AND VENTILATION SYSTEM MEASUREMENTS IN THE
"NORRIS COTTON FEDERAL OFFICE BUILDING IN MANCHESTER
"NEW HAMPSHIRE"
-HUNT (1977)
AIR EXCHANGE RATES WERE MEASURED USING SULFUR HEXAFLOURIDE IN AN ENERGY-SAVING DESIGNED OFFICE BUILDING.
(2.1.18)

3.3.3
"DETERMINATION OF COMBINED AIR EXFILTRATION AND VENTILATION
"RATES IN A NINE-STORY OFFICE BUILDING"
-KELNHOFER, HUNT, DIDION (1976)
DIRECT MEASUREMENTS OF AIR INFILTRATION RATES USING SULFUR

HEXAFLOURIDE AS A TRACER GAS. TRACER INJECTED INTO MAIN TRUNK OF AIR SUPPLY SYSTEM AND SAMPLED IN RETURN LINE.
(2.1.21)

3.3.4
"AIR LEAKAGE MEASUREMENTS OF THE EXTERIOR WALLS OF TALL BUILDINGS"
-SHAW, SANDER, TAMURA (1973)
FOUR HIGH RISE BUILDINGS STUDIED FOR AIR LEAKAGE CHARACTERISTICS, WITH EXPERIMENTAL DATA CORRELATED TO COMPUTER SIMULATION.
ASHRAE TRANS. 1973; 79-II: 40-48

3.3.5
"ANALYSIS OF SMOKE SHAFTS FOR CONTROL OF SMOKE MOVEMENT IN "BUILDINGS"
-TAMURA (1970)
STUDIES THE PERFORMANCE OF SMOKE SHAFTS AS A MEANS FOR REDUCING SMOKE CONCENTRATIONS AND TRANSFER IN TALL BUILDINGS.
ASHRAE TRANS. 1970; 76: 290-297

3.3.6
"STUDIES ON EXTERIOR WALL AIR TIGHTNESS AND AIR INFILTRATION "OF TALL BUILDINGS"
-TAMURA, SHAW (1976)
MEASUREMENTS OF AIR LEAKAGE CHARACTERISTICS OF THE EXTERIOR WALLS OF EIGHT MULTI-STORY OFFICE BUILDINGS IN OTTAWA, CANADA. A METHOD FOR CALCULATING INFILTRATION RATES BY STACK ACTION DEVELOPED.
ASHRAE TRANS. 1976; 82: 122-134

3.3.7
"PRESSURE DIFFERENCES FOR A NINE-STORY BUILDING AS A RESULT "OF CHIMNEY EFFECT AND VENTILATION SYSTEM OPERATION"
-TAMURA, WILSON (1966)
FIRST QUANTITATIVE PRESSURE MEASUREMENTS FOR TALL OFFICE BUILDINGS.
ASHRAE TRANS. 1966; 72: 180-189

3.3.8
"PRESSURE DIFFERENCES CAUSED BY CHIMNEY EFFECT IN THREE "HIGH BUILDINGS"
-TAMURA, WILSON (1967)
FURTHER INVESTIGATION OF OVERALL AIR LEAKAGES AND PATTERNS OF PRESSURE DIFFERENCES INDUCED BY CHIMNEY ACTION AND THE OPERATION OF THE VENTILATING SYSTEMS.
ASHRAE TRANS. 1967; 73: II.1.1-II.1.10

3.3.9
"PRESSURE DIFFERENCE CAUSED BY WIND ON TWO TALL BUILDINGS"
-TAMURA, WILSON (1968)
CONTINUOUS WIND AND PRESSURE RECORDS WERE USED IN A REGRESSION ANALYSIS TO DETERMINE WIND COEFFICIENTS FOR BOTH BUILDINGS.
ASHRAE TRANS. 1968; 74: 170-181

3.4 MODEL ANALYSES AND SIMULATED TESTS

3.4.1
"WIND PRESSURE ON BUILDINGS INCLUDING EFFECTS OF ADJACENT "BUILDINGS"
-BAILEY, VINCENT (1944)
A STUDY OF WIND SPEED AND DISTRIBUTION OF WIND PRESSURE OVER SEVEN BUILDINGS IN WIND TUNNEL TESTS.

(2.3.1)

3.4.2
"COMPUTER ANALYSIS OF STACK EFFECT IN HIGH RISE BUILDING"
-BARRETT, LOCKLIN (1968)
A METHOD FOR PREDICTING THE MAGNITUDE OF POTENTIAL PROBLEMS CAUSED BY STACK EFFECT, INCLUDING UNDESIRABLE PRESSURE DIFFERENTIALS AND AIR FLOWS.
ASHRAE TRANS. 1968; 74E 155-169

3.4.3
"MODEL VERIFICATION OF ANALOGUE INFILTRATION PREDICTIONS"
-BILSBORROW, FRICKE (1975)
SURVEY OF CURRENT METHODS OF CALCULATING NATURAL VENTILATION AND INFILTRATION RATES. STUDIES USING SCALE MODEL BUILDINGS IN WIND TUNNELS TO INVESTIGATE VALIDITY OF THESE METHODS.
(2.3.2)

3.4.4
"HEAT AND MOISTURE FLOW THROUGH OPENINGS BY CONVECTION"
-BROWN, WILSON, SOLVASON (1963)
EQUATIONS AND CHARTS ARE PRESENTED TO CALCULATE HEAT AND MOISTURE TRANSFER THROUGH OPENINGS.
ASHRAE TRANS. 1963; 69E 351-357

3.4.5
"MEASUREMENT OF VENTILATION RATES USING A RADIOACTIVE TRACER"
-COLLINS, SMITH (1955)
TESTS IN AN EXPERIMENTAL HOUSE USING RADIOACTIVE ARGON AS A TRACER TO MEASURE VENTILATION RATES. RESULTS AGREED WITH SIMULTANEOUS MEASUREMENTS USING HYDROGEN.
(2.1.5)

3.4.6
"EXPERIMENTAL CHARACTERIZATION OF VENTILATION SYSTEMS IN "BUILDINGS"
-DRIVAS, SIMMONDS, SHAIR (1972)
TRACER EXPERIMENTS USING SULFUR HEXAFLOURIDE CONDUCTED IN LABORATORY TEST ROOMS TO OBTAIN DATA REGARDING ACTUAL RESIDENCE TIME DISTRIBUTIONS IN ROOMS AND HALLWAYS.
(2.1.8)

3.4.7
"CALCULATION OF INFILTRATION AND TRANSMISSION HEAT "LOSSES IN RESIDENTIAL BUILDINGS BY DIGITAL COMPUTER"
-GABRIELSSON, PORRA (1968)
AN EFFECTIVE AID IN CALCULATING HEAT LOADS, INFILTRATION HEAT LOSS, AND VENTILATION RATES.
J.INST.HEAT.VENT.ENG. 1968; 36E 357-353

3.4.8
"DYNAMIC CHARACTERISTICS OF AIR INFILTRATION"
-HILL, KUSUDA (1975)
TWO OFFICES WERE RETROFITTED AND SET UP AS TEST ROOMS FOR CONTROLLED TRACER GAS EXPERIMENTS TO STUDY AIR INFILTRATION.
(2.1.14)

3.4.9
"AIR INFILTRATION MEASUREMENTS IN A FOUR BEDROOM TOWNHOUSE "USING SULFUR HEXAFLOURIDE AS A TRACER GAS"
-HUNT, BURCH (1975)

CONTROLLED TRACER GAS MEASUREMENTS CARRIED OUT IN A FACTORY PRODUCED TOWNHOUSE REASSEMBLED IN AN ENVIRONMENTAL CHAMBER.
(2.1.19)

3.4.10
"A STUDY OF THE NATURAL VENTILATION OF TALL OFFICE BUILDINGS"
-JACKMAN (1970)
A THEORETICAL STUDY OF THE NATURAL VENTILATION PROCESS USING BOTH ANALOGUE AND DIGITAL TECHNIQUES WITH THE AIM OF PRODUCING A DESIGN METHOD TO ASSESS NATURAL VENTILATION IN BUILDINGS.
J.INST.HEAT.VENT.ENG. 1970; 38= 103-113

3.4.11
"THE CALCULATION OF AIR INFILTRATION RATES CAUSED BY
"WIND AND STACK ACTION FOR TALL BUILDINGS"
-SHAW, TAMURA (1977)
PROCEDURES FOR CALCULATING AIR INFILTRATION RATES WERE DEVELOPED USING WIND PRESSURE DATA FROM WIND TUNNEL TESTS AND THE AID OF A COMPUTER MODEL BUILDING.
(2.3.6)

3.4.12
"FEASIBILITY OF USING MODELS FOR PREDETERMINING NATURAL VENTILATION"
-SMITH (1951)
AIR FLOW PATTERNS ARE STUDIED ON AN EXPERIMENTAL BUILDING AND IN A WIND TUNNEL WITH SCALE MODELS, INCLUDING THE EFFECTS OF A SMALL CHANGE IN WINDOW SIZE AND POSITION.
TEXAS A & M UNIV. 1951; RESEARCH REPORT #25

3.4.13
"COMPUTER ANALYSIS OF SMOKE MOVEMENT IN TALL BUILDINGS"
-TAMURA (1969)
COMPUTER CALCULATIONS OF AIR LEAKAGE RATES RESULTING FROM STACK EFFECTS IN A HYPOTHETICAL 20-STORY BUILDING.
ASHRAE TRANS. 1969; 75= 81-92

3.4.14
"ANALYSIS OF SMOKE SHAFTS FOR CONTROLLED SMOKE MOVEMENT
"IN BUILDINGS"
-TAMURA (1970)
COMPUTER AND FIELD STUDIES TO DETERMINE THE PERFORMANCE OF SMOKE SHAFTS AS A MEANS OF REDUCING SMOKE CONCENTRATION AND TRANSFER IN TALL BUILDINGS.
(3.3.5)

3.4.15
"BUILDING PRESSURES CAUSED BY CHIMNEY ACTION AND MECHANICAL
"VENTILATION"
-TAMURA, WILSON (1967)
ANALYTICAL STUDY OF THE DISTRIBUTION OF PRESSURE DIFFERENCES CAUSED BY CHIMNEY ACTION IN BUILDINGS, AND THE EFFECT OF VARYING EXCESS SUPPLY AND EXHAUST AIR.
ASHRAE TRANS. 1967; 73= II.2.1-II.2.12

3.4.16
"NATURAL VENTING TO CONTROL SMOKE MOVEMENT IN BUILDING
"VIA VERTICAL SHAFTS"
-TAMURA, WILSON (1970)
EXAMINES THE FACTORS THAT EFFECT NATURAL VENTING OF VERTICAL SHAFTS AND VENT SIZE REQUIREMENTS. BASED ON MATHEMATICAL MODELS WITH FIELD MEASUREMENTS ALSO REPORTED.

ASHRAE TRANS. 1970; 76E 279-289

3.4.17
"WIND PROFILES OVER A SUBURBAN SITE AND WIND EFFECTS
ON A HALF FULL-SCALE MODEL BUILDING"
-TORRANCE (1972)
PROFILES OF NATURAL WIND ON A SITE WERE MEASURED AND COMPARED
WITH EFFECTS EXPERIENCED BY THE WIND TUNNEL MODEL.
BUILD. SCI. 1972; 7E 1-12

3.4.18
"NUMERICAL CALCULATION OF ROOM AIR MOVEMENT--ISOTHERMAL
TURBULENT TWO DIMENSIONAL CASE--"
-TSUCHIYA (1976)
DETAILED COMPUTATIONAL PROCEDURE DESCRIBED TOGETHER WITH
TECHNIQUES FOR OBSERVING FLOW PATTERNS EXPERIMENTALLY.
BUILDING RESEARCH INSTITUTE, TOKYO, PAPER #62, JAN. 1975

3.4.19
"EFFECTS OF LANDSCAPE DEVELOPMENT ON THE NATURAL VENTILATION
OF BUILDINGS"
-WHITE (1954)
USES WIND TUNNEL TESTS AND OBSERVATIONS IN THE FIELD TO MEASURE
THE EFFECTS OF TREES, HEDGES, AND SHRUBS ON AIR FLOW AROUND
AND THROUGH BUILDINGS.
TEXAS A & M UNIV. 1954; RESEARCH REPORT #45

3.4.20
"CONTAMINANT DISPERSION AND DILUTION IN A VENTILATED SPACE"
-WEST (1977)
TEST ROOM EXPERIMENTS TO CHARACTERIZE BEHAVIOR OF AIR
CONTAMINANTS WITHIN AN ENCLOSED VENTILATED SPACE, USING
TRACER GAS TECHNOLOGY.
(2.1.27)

3.5 OTHER TEST SPACES

3.5.1
"AIR CHANGE AND AIR TRANSFER IN A HOSPITAL WARD UNIT"
-BAIRD (1965)
INVESTIGATION OF AIR FLOW IN HOSPITAL ROOMS USING
NITROUS OXIDE AS A TRACER GAS. MAIN FACTORS WERE ISOLATED
AND PREDICTION EQUATIONS GIVEN FOR THESE FACTORS. DISCUSSION
ON THE USE OF THESE EQUATIONS FOR THE DESIGN OF HOSPITAL
VENTILATION SYSTEMS.
(2.1.2)

3.5.2
"ANALYSIS OF ABOVEGROUND FALLOUT SHELTER VENTILATION
REQUIREMENTS"
-BASCHIERE, LOKMANHEKIM, MOY, ENGHOLM (1965)
DETERMINES THE MOST SIMPLE ANALYTICAL MODEL THAT CAN
PREDICT THE PSYCHROMETRIC CONDITIONS THAT DEVELOP IN
ABOVEGROUND SHELTERS.
ASHRAE TRANS. 1965; 71E 101-113

3.5.3
"NATURAL VENTILATION OF UNDERGROUND FALLOUT SHELTERS"
-DUCAR (1965)
A METHOD FOR PREDICTING THE NATURAL VENTILATION RATE OF
UNDERGROUND SHELTERS AS A FUNCTION OF AIR TEMPERATURE,

HUMIDITY, AND VENTILATION SYSTEM DESIGN.
ASHRAE TRANS. 1965; 71E 88-100

3.5.4
"RIDGE VENT EFFECTS ON MODEL VENTILATION CHARACTERISTICS"
-FROEHLICH, HELLICKSON, YOUNG (1974)
EVALUATION OF AIR FLOW CHARACTERISTICS AND TEMPERATURE IN A MODEL OF AN OPEN FRONT BEEF CONFINEMENT BUILDING UNDER ACTUAL WEATHER CONDITIONS.
ASAE TRANS. 1975; 18E 690-693

3.5.5
"DIE TECHNIK DER LUFTWECHSELBESTIMMUNG MIT RADIOAKTIVEM
"KRYPTON-85 UND IHRE ANWENDUNG AUF UNTERSUCHUNGEN IM
"STALLEN"
-GOTTLING, DOMBERG, HILLIGER, VOGG (1972) GERMAN
RADIOACTIVE TRACER GAS USED TO MEASURE AIR INFILTRATION RATES IN STABLES.
(2.1.11)

3.5.6
"BACTERIAL CONTAMINATION IN A MODERN OPERATING SUITE"
-HAMBRAEUS, BENGTSSON, LAURELL (1977)
EFFECT OF VENTILATION ON AIRBORNE CONTAMINATION STUDIED IN A NEW OPERATING SUITE, USING POTASSIUM IODIDE PARTICLES AS A TRACER.
(2.1.12)

3.5.7
"CHARACTEIZATION OF BUILDING INFILTRATION BY THE TRACER
"DILUTION METHOD"
-LAGUS (1977)
OUTLINES PROCEDURE FOR TRACER GAS METHOD INVOLVING A MULTIPLE SYSTEM FOR MEASURING AIR EXCHANGE BETWEEN CONSECUTIVE FLOORS IN A BUILDING.
ENERGY 1977; 2E 461-464

3.5.8
"EXPERIMENTELLE STROMUNGSUNTERSUCHUNGEN IM VERSUCHS-
"AUDITORIUM DER ETH ZURICH"
-SPRENGER (1971) GERMAN
INVESTIGATIONS WITH A NEW INJECTION SYSTEM WHICH PRODUCES FRESH AIR VENTILATION ONLY ON DEMAND.
GESUND. ING. 1971; 92E 225-231

4.0 WEATHER INFLUENCES

4.1 TEMPERATURE AND WIND

4.1.1
"ENVIRONMENTAL FACTORS IN THE HEATING OF BUILDINGS"
-ANAPOL'SKAYA, GANDIN (1975)
A STUDY OF HEAT LOSS PATTERNS RESULTING FROM WIND AND TEMPERATURE DIFFERENTIALS AT SEVENTEEN SOVIET SITES.
JOHN WILEY & SONS (NEW YORK, 1975)

4.1.2
"THE EFFECT OF WIND ON ENERGY CONSUMPTION IN BUILDINGS"

-ARENS, WILLIAMS (1977)
DISCUSSES FOUR MECHANISMS BY WHICH THE WIND EFFECTS HEATING
AND COOLING LOADS IN BUILDINGS, PRESENTING THEIR RELATIVE
IMPORTANCES.
ENERGY AND BUILDINGS 1977; 1: 77-84

4.1.3
"MEASUREMENT OF INFILTRATION IN TWO RESIDENCES. PART II
"A COMPARISON OF VARIABLES AFFECTING INFILTRATION"
-BAHNFLETH, MOSELEY, HARRIS (1957)
CORRELATES INFILTRATION RATES TO WIND VELOCITY AND DIRECTION,
AND TEMPERATURE AND PRESSURE DIFFERENTIALS; SITE CONSIDERATIONS
WERE ALSO NOTED.
ASHRAE TRANS. 1957; 63: 453-476

4.1.4
"WIND PRESSURE ON BUILDINGS INCLUDING EFFECTS OF ADJACENT
"BUILDINGS"
-BAILEY, VINCENT (1944)
WIND TUNNEL EXPERIMENTS TO DETERMINE EFFECTS OF WIND SPEED
ON PRESSURE DISTRIBUTION.
(2.3.1)

4.1.5
"COMPUTER ANALYSIS OF STACK EFFECT IN HIGH-RISE BUILDINGS"
-BARRETT, LOCKLIN (1968)
A COMPUTER PROGRAM IS USED TO CALCULATE TYPICAL AIR FLOW
PATHS TO DETERMINE AND PREDICT PROBLEMS CAUSED BY STACK EFFECT.
(3.4.2)

4.1.6
"FIELD MEASUREMENTS OF AIR INFILTRATION IN TEN ELECTRICALLY-
"HEATED HOUSES"
-COBLENTZ, ACHENBACH (1963)
INFILTRATION RATES MEASURED UNDER A VARIETY OF WIND AND
TEMPERATURE CONDITIONS, USING TRACER GAS TECHNIQUE.
(3.1.3)

4.1.7
"VENTILATION OF AN ENCLOSURE THROUGH A SINGLE OPENING"
-COCKROFT, ROBERTSON (1976)
STUDIES THE MECHANISM OF AIR EXCHANGE AT A SINGLE WALL OPENING
DUE TO WIND FLUCTUATIONS.
BUILD. ENVIRON. 1976; 11: 29-35

4.1.8
"THE APPLICATION OF STATISTICAL CONCEPTS TO THE WIND
"LOADING OF STRUCTURES"
-DAVENPORT (1961)
EXAMINES THE BEHAVIOR OF STRUCTURES WHEN EXPOSED TO
TURBULENT, GUSTY WINDS.
PROC. INST. CIV. ENG. 1961; 19: 449-471

4.1.9
"EXPERIMENTAL STUDIES IN NATURAL VENTILATION OF HOUSES"
-DICK (1949)
VARIATIONS IN AIR CHANGE RATE WERE FOUND MAINLY DUE TO WIND
SPEED AND DIRECTION, AND THAT TEMPERATURE DIFFERENCES WERE
A SECONDARY FACTOR.
(3.1.4)

4.1.10
"THE FUNDAMENTALS OF NATURAL VENTILATION OF HOUSES"
-DICK (1950)
INCLUDES A DISCUSSION ON THE EFFECTS OF WIND AND TEMPERATURE DIFFERENCE ON THE VENTILATION OF AN EXPOSED HOUSE.
J.INST.HEAT.VENT.ENG. 1950; 18E 123-134

4.1.11
"VENTILATION RESEARCH IN OCCUPIED HOUSES"
-DICK, THOMAS (1951)
CONTINUATION OF STUDIES ON NATURAL VENTILATION, INCLUDING FURTHER MEASUREMENTS ON AIR EXCHANGE RATES AND A DISCUSSION ON THE WINDOW OPENING HABITS OF OCCUPANTS.
(3.1.5)

4.1.12
"AIR CHANGE MEASUREMENTS USING A TRACER GAS TECHNIQUE"
-DOEFFINGER (1975)
AIR CHANGE RATES MEASURED OVER VARYING ENVIRONMENTAL AND BUILDING CONDITIONS FOR DETERMINING BUILDING ENERGY CONSUMPTION.
(2.1.7)

4.1.13
"RESIDENTIAL ENERGY CONSERVATION--THE TWIN RIVERS PROJECT"
-HARRJE, SOCOLOW, SONDEREGGER (1977)
INCLUDES CORRELATION OF WIND AND TEMPERATURE DIFFERENTIALS ON AIR INFILTRATION AND ENERGY CONSUMPTION, AND USES WIND TUNNEL TESTS FOR PRESSURE MEASUREMENTS.
(3.1.8)

4.1.14
"DYNAMIC CHARACTERISTICS OF AIR INFILTRATION"
-HILL, KUSUDA (1975)
INFILTRATION DATA GATHERED WITH TRACER GAS EXPERIMENTS AND CORRELATED WITH WIND SPEED AND THE PRESSURE DIFFERENCE EXERTED ON AN ENCLOSURE.
(2.1.14)

4.1.15
"VENTILATION MEASUREMENTS IN HOUSES AND THE INFLUENCE OF "WALL VENTILATORS"
-HOWARD (1966)
VENTILATION RATES WERE MEASURED IN SIX HOUSES WITH DATA TAKEN ON WIND SPEED AND DIRECTION.
(2.1.16)

4.1.16
"AIR INFILTRATION MEASUREMENTS IN A FOUR BEDROOM TOWNHOUSE "USING SULFUR HEXAFLOURIDE AS A TRACER GAS"
-HUNT, BURCH (1975)
CONTROLLED MEASURMENTS OF AIR INFILTRATION RATES UNDER VARYING TEMPERATURES, WITH ZERO WIND VELOCITY.
(2.1.19)

4.1.17
"HEAT LOSS IN BUILDINGS AS A RESULT OF INFILTRATION"
-JACKMAN (1974)
A MULTIPLE OF WIND SPEED AND INDOOR-OUTDOOR TEMPERATURE DIFFERENCE WAS USED AS A MEASURE OF INFILTRATION HEAT LOSS CAUSED BY WIND.
BUILD. SERV. ENG. 1974; 42E 6-15

4.1.18
"STATISTICAL ANALYSES OF AIR LEAKAGE IN SPLIT LEVEL
"RESIDENCES"
-LASCHOBER, HEALY (1964)
DATA WAS COLLECTED IN TWO HOUSES AND ANALYZED TO DETERMINE
WHETHER INFILTRATION COULD BE CORRELATED TO OUTDOOR
TEMPERATURE AND WIND CONDITIONS.
(3.1.14)

4.1.19
"THE VARIATION OF INFILTRATION RATE WITH RELATIVE HUMIDITY
"IN A FRAME BUILDING"
-LUCK, NELSON (1977)
LOCALLY MEASURED WEATHER AND DATA TAKEN FROM WEATHER
BUREAU WERE COMPARED AND USED TO STUDY INFILTRATION
AND HUMIDITY IN A MINNESOTA HOUSE.
(3.1.15)

4.1.20
"WIND EFFECT ON THE AIR MOVEMENT INSIDE BUILDINGS"
-MALINOWSKI (1971)
A STUDY OF THE EFFECT OF THE WIND ON DIFFERENT MODELS
OF AIR FLOW THROUGH SMALL OPENINGS, INCLUDING THROUGH
FLOW, PULSATING FLOW, TURBULENT FLOW, AND DIFFUSE FLOW.
PROCEEDINGS OF THE THIRD INTERNATIONAL CONFERENCE ON
WIND EFFECTS ON BUILDINGS AND STRUCTURES
TOKYO, 1971; 125-134

4.1.21
"WIND AND TREES--AIR INFILTRATION EFFECTS ON ENERGY
"IN HOUSING"
-MATTINGLY, PETERS (1975)
SMOKE TUNNEL TESTS WERE CONDUCTED TO EXAMINE THE WAYS IN
WHICH WIND INFLUENCES INFILTRATION ENERGY LOSSES IN HOUSING.
(2.3.5)

4.1.22
"WIND, TEMPERATURE, AND NATURAL VENTILATION"
-SINDEN (1976)
EXAMINES THE INTERACTION OF WIND AND TEMPERATURE EFFECTS IN
DETERMINING AIR INFILTRATION RATES.
PRINCETON UNIV. TWIN RIVERS PROJECT -NOTE 6, JUNE 1976

4.1.23
"DYNAMIC MODELS OF HOUSE HEATING BASED ON EQUIVALENT
"THERMAL PARAMETERS"
-SONDEREGGER (1977)
INCLUDES DESCRIPTION OF FREQUENCY SPECTRUM OF OUTDOOR
TEMPERATURE FLUCTUATIONS.
PH.D. DISSERTATION, PRINCETON UNIVERSITY, SEPT. 1977

4.1.24
"AIR LEAKAGE AND PRESSURE MEASUREMENTS ON TWO OCCUPIED
"HOUSES"
-TAMURA, WILSON (1964)
MEASURED AIR LEAKAGE WAS RELATED TO WEATHER CONDITIONS
AND TO FURNACE OPERATION. MEASUREMENTS OF WIND VELOCITY
AND DIRECTION RELATED TO PRESSURE DIFFERENCES ACROSS
THE WALLS IN BOTH SUMMER AND WINTER CONDITIONS.
(3.1.19)

4.1.25
"PRESSURE DIFFERENCES CAUSED BY WIND ON TWO TALL BUILDING"
-TAMURA, WILSON (1968)
CONTINUOUS WIND AND PRESSURE RECORDS WERE OBTAINED, AND WITH THE AID OF A DIGITAL COMPUTER, WIND PRESSURE COEFFICIENTS WERE DETERMINED FOR BOTH BUILDINGS.
(3.3.9)

4.1.26
"WIND PROFILES OVER A SUBURBAN SITE AND WIND EFFECTS "ON A HALF FULL-SCALE MODEL BUILDING"
-TORRANCE (1972)
WIND PROFILES WERE MEASURED WITH RESULTING PRESSURE EFFECTS RECORDED. THREE TEST POSITIONS OF THE MODEL BUILDING WERE STUDIED.
(3.4.17)

4.1.27
"VENTILATION THROUGH OPENINGS ON ONE WALL ONLY"
-WARREN (1977)
COMPARES EFFECTIVENESS OF DIFFERENT AIR EXCHANGE MECHANISMS WHEN THEY ACT ON ONE OR MORE WALL OPENINGS IN A SINGLE WALL.
BUILDING RESEARCH ESTABLISHMENT REPORT, AUGUST 1977

4.2 HUMIDITY

4.2.1
"HEAT AND MOISTURE FLOW THROUGH OPENINGS BY CONVECTION"
-BROWN, WILSON, SOLVASON (1963)
RELATIONSHIPS OF HEAT AND MOISTURE TRANSFER ARE PRESENTED, WITH CHARTS TO FACILITATE THE CALCULATIONS.
(3.4.4)

4.2.2
"A STUDY OF HUMIDITY VARIATIONS IN CANADIAN HOUSES"
-KENT, HANDEGORD, ROBINSON (1966)
TEMPERATURE AND HUMIDITY LEVELS WERE RECORDED AND OCCUPANT HABITS OBSERVED TO UNDERSTAND INSIDE RELATIVE HUMIDITY CONDITIONS.
ASHRAE TRANS. 1966; 72-II: II.1.1-II.1.8

4.2.3
"THE VARIATION OF INFILTRATION RATE WITH RELATIVE HUMIDITY "IN A FRAME BUILDING"
-LUCK, NELSON (1977)
INVESTIGATES THE EFFECTS OF INFILTRATION ON INSIDE RELATIVE HUMIDITY FOR POSSIBLE ENERGY CONSERVATION MEASURES.
(2.1.24)

4.2.4
"THE ENERGY COST OF HUMIDIFICATION"
-SHELTON (1976)
DISCUSSES THE ROLE OF AIR INFILTRATION IN AFFECTING RELATIVE HUMIDITY, AND GIVES EXAMPLES OF TYPICAL ENERGY COSTS IN HUMIDIFYING A ROOM.
ASHRAE J. 1976; 18: 52-55

4.2.5
"MEASUREMENT OF AIR-TIGHTNESS OF HOUSES"
-STRICKER (1975)
ACTUAL LEAKAGE AREAS OF HOUSES WERE CALCULATED TO

UNDERSTAND PROBLEMS OF HIGH INDOOR HUMIDITY.
(2.2.8)

4.3 TERRAIN

4.3.1
"THE APPLICATION OF STATISTICAL CONCEPTS TO THE WIND LOADING
"OF STRUCTURES"
-DAVENPORT (1961)
DEVELOPS AN EXPRESSION FOR THE SPECTRUM OF GUSTINESS CLOSE TO
THE GROUND WHICH TAKES INTO ACCOUNT ROUGHNESS OF THE TERRAIN.
(4.1.8)

4.3.2
"EXPERIMENTAL STUDIES IN NATURAL VENTILATION OF HOUSES"
-DICK (1949)
AIR INFILTRATION RATES MEASURED FOR TWENTY HOUSES BUILT
IN TWO PARALLEL ROWS UNSHELTERED BY TREES OR BUILDINGS.
(3.1.4)

4.3.3
"RESIDENTIAL ENERGY CONSERVATION--THE TWIN RIVERS PROJECT"
-HARRJE, SOCOLOW, SONDEREGGER (1977)
AIR INFILTRATION RATES STUDIED FOR TWENTY-NINE HOUSES
LOOKING AT EFFECTS OF ADJACENT TREES AND BUILDINGS.
(3.1.8)

4.3.4
"WIND FLOW IN AN URBAN AREA"
-JONES, WILSON (1968)
COMPARES WIND FLOW PATTERNS AS MEASURED IN A RELATIVELY OPEN
AREA IN LIVERPOOL TO A 1/500 SCALE MODEL OF THE SAME SITE
IN A WIND TUNNEL.
BUILD. SCI. 1968; 3= 31-40

4.3.5
"WIND PROFILES OVER A SUBURBAN SITE AND WIND EFFECTS
"ON A HALF FULL-SCALE BUILDING"
-TORRANCE (1972)
A MODEL BUILDING WAS TESTED IN THE FIELD WITH THREE
DIFFERENT ORIENTATIONS TO STUDY WIND PROFILES AND
PRESSURE DISTRIBUTIONS.
(3.4.17)

5.0 BUILDING COMPONENTS

5.1 WINDOWS

5.1.1
"ENERGY MANAGEMENT AND VENTILATION"
-ADAMSON (1970)
DISCUSSES THE EFFECTS OF OPEN WINDOWS ON INFILTRATION RATES.
LUND UNIVERSITY REPORT, 1977

5.1.2
"VENTILATION, A BEHAVIORAL APPROACH"
-BRUNDRETT (1976)
BEHAVIORAL STUDIES OF WINDOW OPENING HABITS OF FAMILIES
IN HOUSES.

CIB CONFERENCE ON ENERGY IN BUILDINGS
BUILDING RESEARCH ESTABLISHMENT, WATFORD APRIL 1976

5.1.3
'COMBINED THERMAL AND AIR LEAKAGE PERFORMANCE OF
'DOUBLE WINDOWS'
-BURSEY, GREEN (1970)
WINDOWS WERE INSTALLED IN A HOT BOX CALORIMETER WITH A SYSTEM FOR CREATING A PRESSURE DIFFERENCE ACROSS THE WINDOW. TESTS MADE TO DETERMINE OVERALL U VALUE, AIR LEAKAGE RATES AND THE TEMPERATURE INDEX.
(2.3.3)

5.1.4
'THERMAL PERFORMANCE OF IDEALIZED DOUBLE WINDOWS,
'UNVENTED'
-CHRISTENSEN, BROWN, WILSON (1964)
INSIDE SURFACE TEMPERATURES MEASURED ON WINDOWS INSTALLED IN A HOT BOX APPARATUS. CONTROLLED NATURAL CONVECTION ON WARM SIDE WITH FORCED CONVECTION ON COOL SIDE.
ASHRAE TRANS. 1964; 70E 408-418

5.1.5
'FIELD MEASUREMENTS OF AIR INFILTRATION IN TEN ELECTRICALLY-
'HEATED HOUSES'
-COBLENTZ, ACHENBACH (1963)
CRACK LENGTHS COMPUTED FOR ALL WINDOWS TO MEASURE AIR INFILTRATION RATE, COMPARED TO TRACER GAS EXPERIMENTAL RESULTS FOR THE SAME HOUSES.
(3.1.3)

5.1.6
'EXPERIMENTAL STUDIES IN NATURAL VENTILATION OF HOUSES'
-DICK (1949)
TESTS RUN WITH WINDOWS CLOSED FOR A WINTER WITH SIMULATED OCCUPANCY DEMANDS ON HEATING SYSTEMS.
(3.1.4)

5.1.7
'VENTILATION RESEARCH IN OCCUPIED HOUSES'
-DICK, THOMAS (1951)
DAILY OBSERVATIONS OF THE NUMBER AND POSITION OF OPEN WINDOWS AND THEIR DEGREE OF OPENING WERE TAKEN FROM OCTOBER TO APRIL, AND RELATED TO INFILTRATION RATES.
(3.1.5)

5.1.8
'ADVENTITIOUS VENTILATION OF HOUSES'
-HARRIS-BASS, KAVARANA, LAWRENCE (1974)
MEASUREMENTS OF THE EFFECT OF WEATHERSTRIPPING AND DOUBLE GLAZING THE WINDOWS ON THE VENTILATION RATE OF A ROOM.
(2.3.4)

5.1.9
'RESIDENTIAL ENERGY CONSERVATION - THE TWIN RIVERS PROJECT'
-HARRJE, SOCOLOW, SONDEREGGER (1977)
INCLUDES THE EFFECT OF WINDOW OPENING ON INFILTRATION RATES.
(3.1.8)

5.1.10
'DYNAMIC CHARACTERISTICS OF AIR INFILTRATION'
-HILL, KUSUDA (1975)
PRESSURE DROP WAS MEASURED ACROSS WINDOWS TO RELATE INFILTRATION

AND WIND SPEED. CALIBRATED PLASTIC TEST WINDOWS WERE USED FOR THE EXPERIMENTS.
(2.1.14)

5.1.11
"VENTILATION OF BUILDINGS AND ITS DISTURBANCES"
-HONMA (1975)
PRESENTS STUDIES OF FLOW AS A FUNCTION OF PRESSURE THROUGH SMALL CRACKS.
(2.1.15)

5.1.12
"AIR FLOW THROUGH CRACKS"
-HOPKINS, HANSFORD (1974)
CALCULATED AND MEASURED FLOW THROUGH DIFFERENT TYPES OF CRACKS WHICH SIMULATE THE BEHAVIOR OF CRACKS AROUND WINDOWS.
BUILD. SERV. ENG. 1974; 42= 123-131

5.1.13
"AIR LEAKAGE THROUGH THE OPENINGS IN BUILDINGS"
-HOUGHTEN, SCHRADER (1924)
INFILTATION RATES WERE MEASURED THROUGH A TEST WINDOW OPENED DIFFERENT AMOUNTS, CLOSED, LOCKED, AND WEATHERSTRIPPED.
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LUND INSTITUTE OF TECHNOLOGY=
DEPARTMENT OF BUILDING SCIENCE REPORT, 1977.

5.1.18
"AIR LEAKAGE VALUES FOR RESIDENTIAL WINDOWS"
-SASAKI, WILSON (1965)

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-SCHUTRUM, OZISIK, BAKER, HUMPHREYS (1961)
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-HARRJE, SOCOLOW, SONDEREGGER (1977)
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ENGINEERING FOR POWER 1977; 99= 329-334

5.3.4
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ASHRAE TRANS. 1977; 83=

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"AIR LEAKAGE AND PRESSURE MEASUREMENTS IN TWO OCCUPIED "HOUSES"
-TAMURA, WILSON (1964)
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"VENTILATION--DESIGN CONSIDERATIONS"
-TIPPING, HARRIS-BASS, NEVRALA (1974)
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BUILD. SERV. ENG. 1974; 42E 132-141

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-WILSON (1961)
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PRINCETON UNIV. TWIN RIVERS PROJECT≡ NOTE 3. 1977

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"WIND AND TREES--AIR INFILTRATION EFFECTS ON ENERGY
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-MATTINGLY, PETERS (1975)
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-BASNETT, MOULD, SIVIOUR (1975)
A MATHEMATICAL MODEL USED TO CALCULATE AND COMPARE THERMAL BEHAVIOR IN WELL INSULATED HOUSES.
ENERGY AND HOUSING, SPECIAL SUPPLEMENT TO BUILDING SCIENCE, 1975

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CANADIAN JOUR. CHEM. ENG. 1959; 37≡ N 3 105-112

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HUD PDR 117 MAY 1975

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ENERGY AND BUILDINGS 1977; 1= 69-76

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"A STUDY OF NATURAL VENTILATION IN TALL OFFICE BUILDINGS"
-JACKMAN (1970)
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LITERATURE SURVEY REPORT
BIBLIOGRAPHY INDEX
PREPARED BY R.C. DIAMOND AND D.T. GRIMSRUD
LAWRENCE BERKELEY LABORATORY, JANUARY 1978

-ADAMSON (1977)
"ENERGY MANAGEMENT AND VENTILATION"
LUND UNIVERSITY REPORT, 1977
5.1.1

-ANAPOL'SKAYA, GANDIN (1975)
"ENVIRONMENTAL FACTORS IN THE HEATING OF BUILDINGS"
JOHN WILEY & SONS (NEW YORK, 1975)
4.1.1

-ANGUS (1949)
"THE STUDY OF AIR FLOW, VENTILATION, AND AIR MOVEMENT IN
"SMALL ROOMS AS EFFECTED BY OPEN FIRES AND VENTILATION DUCTS"
J.INST.HEAT.VENT.ENG. 1949; 17= 378-413
5.4.1

-ANSI/ASTM (1976)
"STANDARD TEST METHOD FOR RATE OF AIR LEAKAGE THROUGH
"EXTERIOR WINDOWS, CURTAIN WALLS, AND DOORS"
ASTM STANDARD E283-73
2.2.1

-ARENS, WILLIAMS (1977)
"THE EFFECT OF WIND ON ENERGY CONSUMPTION IN BUILDINGS"
ENERGY AND BUILDINGS 1977; 1= 77-84
4.1.2

-ASHRAE HANDBOOK OF FUNDAMENTALS (1977)
"INFILTRATION AND NATURAL VENTILATION" CHAPTER 21
1.0.1

-BAHNFLETH, MOSELEY, HARRIS (1957)
"MEASUREMENT OF INFILTRATION IN TWO RESIDENCES" PART ONE
ASHRAE TRANS. 1957; 63= 439-452
2.1.1
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-BAHNFLETH, MOSELEY, HARRIS (1957)
"MEASUREMENT OF INFILTRATION IN TWO RESIDENCES. PART II
"A COMPARISON OF VARIABLES AFFECTING INFILTRATION"
ASHRAE TRANS. 1957; 63= 453-476
4.1.3
6.2.1

-BAILEY, VINCENT (1944)
"WIND PRESSURE ON BUILDINGS INCLUDING EFFECTS OF ADJACENT
"BUILDINGS"
J.INST.CIV.ENG. 1943; 20= 243-275
2.3.1
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-BAIRD (1969)
"AIR CHANGE AND AIR TRANSFER IN A HOSPITAL WARD UNIT"

BUILD. SCI. 1969; 3= 113-123
2.1.2
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-BARGETZI, HARTMANN, PFIFFNER (1977) GERMAN
"MESSUNG DES NATURLICHEN LUFTWECHSELS IN NICHTKLIMATISIERTEN
"WOHNRAUMEN "
SCHWEIZ. BAUZTG. 1977; 95= HEFT 14= 3-7
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-BARRETT, LOCKLIN (1968)
"COMPUTER ANALYSIS OF STACK EFFECT IN HIGH RISE BUILDING"
ASHRAE TRANS. 1968; 74= 155-169
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-BASCHIERE, LOKMANHEKIM, MOY, ENGHOLM (1965)
"ANALYSIS OF ABOVEGROUND FALLOUT SHELTER VENTILATION
"REQUIREMENTS"
ASHRAE TRANS. 1965; 71= 101-113
3.5.2

-BASNETT, MOULD, SIVIOUR (1975)
"SOME EFFECTS OF VENTILATION RATE, THERMAL INSULATION,
"AND MASS ON THE THERMAL PERFORMANCE OF HOUSES IN
"SUMMER AND WINTER"
ENERGY AND HOUSING, SPECIAL SUPPLEMENT TO BUILDING SCIENCE, 1975
6.1.2

-BEYEA, HARRJE, SINDEN (1977)
"ENERGY CONSEVATION IN AN OLD THREE STORY APARTMENT COMPLEX"
ENERGY USE MANAGEMENT, PERGAMON, NY 1977; I= 373-383
3.2.1

-BILSBORROW, FRICKE (1975)
"MODEL VERIFICATION OF ANALOGUE INFILTRATION PREDICTIONS"
BUILD. SCI. 1975; 10= 217-230
2.3.2
3.4.3

-BROWN, WILSON, SOLVASON (1963)
"HEAT AND MOISTURE FLOW THROUGH OPENINGS BY CONVECTION"
ASHRAE TRANS. 1963; 69= 351-357
3.4.4
4.2.1

-BRUNDRETT (1976)
"VENTILATION, A BEHAVIORAL APPROACH"
CIB CONFERENCE ON ENERGY IN BUILDINGS
BUILDING RESEARCH ESTABLISHMENT, APRIL 1975
5.1.2

-BURSEY, GREEN (1970)
"COMBINED THERMAL AND AIR LEAKAGE PERFORMANCES OF
"DOUBLE WINDOWS"
ASHRAE TRANS. 1970; 76= 215-226
2.3.3
5.1.3

-CHOLETTE, CLOUTIER (1959)

"MIXING EFFICIENCY DETERMINATIONS FOR CONTINUOUS FLOW SYSTEMS"
CANADIAN JOUR. CHEM. ENG. 1959; 37= N 3 105-112
6.1.3

-CHRISTENSEN, BROWN, WILSON (1964)
"THERMAL PERFORMANCE OF IDEALIZED DOUBLE WINDOWS,
"UNVENTED"
ASHRAE TRANS. 1964; 70= 408-418
5.1.4

-COBLENTZ, ACHENBACH (1957)
"DESIGN AND PERFORMANCE OF A PORTABLE INFILTRATION METER"
ASHRAE TRANS. 1957; 63= 477-482
2.1.4

-COBLENTZ, ACHENBACH (1963)
"FIELD MEASUREMENTS OF AIR INFILTRATION IN TEN ELECTRICALLY
"HEATED HOUSES"
ASHRAE TRANS. 1963; 69= 358-365
3.1.3
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-COCKROFT, ROBERTSON (1976)
"VENTILATION OF AN ENCLOSURE THROUGH A SINGLE OPENING"
BUILD. ENVIRON. 1976; 11= 29-35
4.1.7

-COLLINS, SMITH (1955)
"MEASUREMENT OF VENTILATION RATES USING A RADIOACTIVE TRACER'
J.INST.HEAT.VENT.ENG. 1949; 17= 420-465
2.1.5
3.4.5

-DAVENPORT (1961)
"THE APPLICATION OF STATISTICAL CONCEPTS TO THE WIND
"LOADING OF STRUCTURES"
PROC. INST. CIV. ENG. 1961; 19= 449-471
4.1.8
4.3.1

-DICK (1949)
"EXPERIMENTAL STUDIES IN NATURAL VENTILATION OF HOUSES"
J.INST.HEAT.VENT.ENG. 1949; 17= 420-465
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-DICK (1950)
"MEASUREMENTS OF VENTILATION USING TRACER GAS TECHNIQUES"
HEAT.PIPING AIR COND. 1950; 22= 131-137
2.1.6
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-DICK, THOMAS (1951)
VENTILATION RESEARCH IN OCCUPIED HOUSES"
J.INST.HEAT.VENT.ENG. 1951; 19= 306-325

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-DOEFFINGER (1976)
"AIR CHANGE MEASUREMENTS USING A TRACER GAS TECHNIQUE"
PENN.STATE U. REPORT-DEPT. OF ARCH.ENG. MARCH 1976
2.1.7
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-DRIVAS, SIMMONDS, SHAIR (1972)
"EXPERIMENTAL CHARACTERIZATION OF VENTILATION SYSTEMS
"IN BUILDINGS "
ENVIRON. SCI. TECHNOL. 1972; 6≡ 609-614
2.1.8
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-DUCAR (1965)
"NATURAL VENTILATION OF UNDERGROUND FALLOUT SHELTERS"
ASHRAE TRANS. 1965; 71≡ 88-100
3.5.3

-DUTT (1977)
"THE EFFECT OF MATERIAL POROSITY ON AIR INFILTRATION"
PRINCETON UNIV. TWIN RIVERS PROJECT≡ NOTE 3. 1977
5.5.1

-ELKINS, WENSMAN (1971)
"NATURAL VENTILATION OF MODERN TIGHTLY CONSTRUCTED HOUSES"
AGA CONFERENCE ON NATURAL GAS RESEARCH AND TECHNOLOGY,CHICAGO 2/28-3/3, 1971
2.1.9
3.1.6
6.2.3

-FOORD (1973)
"USE OF GAS AND PARTICLE TRACERS IN THE STUDY OF INFECTION
"TRANSMISSION"
PROCEEDINGS OF FOURTH INTERNATIONAL SYMPOSIUM ON AEROBIOLOGY
HELD AT TECHNICAL UNIVERSITY AT ENSCHEDE, THE NETHERLANDS
OOSTHOEK PUB. CO. UTRECHT 1973 450-454
ED. J.F. PH. HERS & K.C. WINKLER
2.1.10

-FROEHLICH, HELLICKSON, YOUNG (1974)
"RIDGE VENT EFFECTS ON.MODEL VENTILATION CHARACTERISTICS"
ASAE TRANS. 1975; 18≡ 690-693
3.5.4
5.4.4

-GABRIELSSON, PORRA (1968)
"CALCULATION OF INFILTRATION AND TRANSMISSION HEAT
"LOSSES IN RESIDENTIAL BUILDINGS BY DIGITAL COMPUTER"
J.INST.HEAT.VENT.ENG. 1968; 36≡ 357-358
3.4.7
6.1.4

-GOTTLING, DOMBERG, HILLEGER, VOGG (1972) GERMAN
"DIE TECHNIK DER LUFTWECHSELBESTIMMUNG MIT RADIOAKTIV KRYPTON-85

"UND IHRE ANWENDUNG AUF UNTERSUCHUNGEN IN STALLEN"
GESUND. ING. 1972; 93: 16-20
2.1.11
3.5.5

-GRAHAM (1977) MASTER'S THESIS
"INFRASONIC IMPEDANCE MEASUREMENTS OF BUILDINGS FOR AIR
"LEAKAGE DETERMINATION"
M.S. THESIS, SYRACUSE UNIV. 1977
2.2.2
3.1.7

-HAMBERAEUS, BENGTSSON, LAURELL (1977)
"BACTERIAL CONTAMINATION IN A MODERN OPERATING SUITE. PART ONE:
"EFFECT OF VENTILATION ON AIRBORNE PARTICLES"
J. HYG. CAMB. 1977; 79: 121-132
2.1.12
3.5.6

-HARRIS-BASS, KAVARANA, LAWRENCE (1974)
"ADVENTITIOUS VENTILATION OF HOUSES"
BUILD. SERV. ENG. 1974; 42: 106-111
2.3.4
5.1.8
5.2.3

-HARRJE, GROT (1977)
"AUTOMATED AIR INFILTRATION MEASUREMENTS AND IMPLICATIONS
"FOR ENERGY CONSERVATION"
PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON ENERGY USE MANAGEMENT
(TUCSON, AZ, OCT. 1977) NEW YORK; PERGAMON 457-464
2.1.13

-HARRJE, SOCOLOW, SONDEREGGER (1977)
"RESIDENTIAL ENERGY CONSERVATION--THE TWIN RIVERS PROJECT"
ASHRAE TRANS. 1977; 83(I):
3.1.8
4.1.13
4.3.3
5.1.9
5.2.4
5.3.2

-HILL, KUSUDA (1975)
"DYNAMIC CHARACTERISTICS OF AIR INFILTRATION"
ASHRAE TRANS. 1975; 81: 168-185
2.1.14
3.4.8
4.1.14
5.1.10

-HITCHEN, WILSON (1967)
"REVIEW OF EXPERIMENTAL TECHNIQUES FOR THE INVESTIGATION
"OF NATURAL VENTILATION IN BUILDINGS "
BUILD. SCI. 1967; 2: 59-82.
1.0.2

-HITTMAN ASSOCIATES (1975)
"TECHNOLOGY ASSESSMENT OF RESIDENTIAL ENERGY CONSERVATION
"INNOVATIONS"
HUD PDR 117 MAY 1975
6.1.5

-HONMA (1975)
"VENTILATION OF BUILDINGS AND ITS DISTURBANCES"
FAIBO GRAFISKA, STOCKHOLM (1975)
2.1.15
3.3.1
5.1.11

-HOPKINS, HANSFORD (1974)
"AIR FLOW THROUGH CRACKS"
BUILD. SERV. ENG. 1974; 42= 123-131
5.1.12

-HOUGHTEN, SCHRADER (1924)
"AIR LEAKAGE THROUGH THE OPENINGS IN BUILDINGS"
ASHRAE TRANS. 1924; 30= 105-120
2.2.3
5.1.13

-HOWARD (1966)
"VENTILATION MEASUREMENTS IN HOUSES AND THE INFLUENCE OF
"WALL VENTILATORS"
BUILD. SCI. 1966; 1= 251-257
2.1.16
3.1.9
4.1.15
5.4.5
6.2.4

-HOWLAND, KIMBER, LITTLEJOHN (1960)
"MEASUREMENTS OF AIR MOVEMENTS IN A HOUSE USING A
"RADIOACTIVE TRACER GAS"
J.INST.HEAT.VENT.ENG. 1960; 28= 57-71
2.1.17
3.1.10
5.4.6

-HUNT (1977)
"AIR EXCHANGE AND VENTILATION SYSTEM MEASUREMENTS IN THE
"NORRIS COTTON FEDERAL OFFICE BUILDING IN MANCHESTER
"NEW HAMPSHIRE"
REPORT OF TEST TO ERDA 1977;
2.1.18
3.3.2

-HUNT, BURCH (1975)
"AIR INFILTRATION MEASUREMENTS IN A FOUR-BEDROOM TOWNHOUSE
"USING SULFUR HEXAFLOURIDE AS A TRACER GAS"
ASHRAE TRANS. 1975; 81= 186-201
2.1.19
3.4.9
4.1.16
5.2.5
6.2.5

-HUNT, PORTERFIELD, ONDRIS (1977)
"AIR LEAKAGE MEASUREMENTS IN THREE APARTMENT HOUSES IN THE
"CHICAGO AREA"
NATIONAL BUREAU OF STANDARDS REPORT 1977
2.2.4
3.2.4

-HUTCHINSON (1977)
"ENERGY SAVINGS DUE TO CHANGES IN DESIGN OF VENTILATION
"AND AIR FLOW SYSTEMS"
ENERGY AND BUILDINGS 1977; 1= 69-76
6.1.6

-IHVE GUIDE BOOK A (1970)
"AIR INFILTRATION" SECTION A4
1.0.3

-JACKMAN (1970)
"A STUDY OF THE NATURAL VENTILATION OF TALL OFFICE BUILDINGS"
J.INST.HEAT.VENT.ENG. 1970; 38= 103-118
3.4.10
6.1.7

-JACKMAN (1974)
"HEAT LOSS IN BUILDINGS AS A RESULT OF INFILTRATION"
BUILD. SERV. ENG. 1974; 42= 6-15
4.1.17

-JANSSEN, BONNE (1977)
"IMPROVEMENT OF SEASONAL EFFICIENCY OF RESIDENTIAL HEATING SPACES"
ENGINEERING FOR POWER 1977; 99= 329-334
5.3.3

-JANSSEN, GLATZEL, TORBORG, BONNE (1977)
"INFILTRATION IN RESIDENTIAL HOUSES"
ASME SYMPOSIUM PROCEEDINGS, ATLANTA, GA., NOV. 1977
2.1.20
3.1.11
5.3.4

-JANSSEN, TORBORG, BONNE (1977)
"MEASUREMENT OF HEATING SYSTEM DYNAMICS FOR COMPUTATION
"OF SEASONAL EFFICIENCY"
ASHRAE TRANS. 1977; 83=
5.3.5

-JENNINGS, ARMSTRONG (1971)
"VENTILATION THEORY AND PRACTICE"
ASHRAE TRANS. 1971, 77= 50-60
1.0.4

-JONES (1968)
"A REVIEW OF THE LITERATURE ON THE STRUCTURE OF WIND
"TURBULENCE, WITH SPECIAL REGARD TO ITS EFFECT ON BUILDINGS "
BUILD. SCI. 1968; 3= 41-50
1.0.5

-JONES, WILSON (1968)
"WIND FLOW IN AN URBAN AREA"
BUILD. SCI. 1968; 3= 31-40
4.3.4

-JORDAN, ERICKSON, LEONARD (1963)
"INFILTRATION MEASUREMENTS IN TWO RESEARCH HOUSES"
ASHRAE TRANS. 1963; 69= 344-350
3.1.12
5.1.14
5.2.6
5.4.7

-KELNHOFER, HUNT, DIDION (1976)
"DETERMINATION OF COMBINED AIR EXFILTRATION AND VENTILATION
"RATES IN A NINE-STORY OFFICE BUILDING"
PROCEEDINGS OF CONFERENCE ON IMPROVING EFFICIENCY AND PERFORMANCE
OF HVAC EQUIPMENT AND SYSTEMS FOR COMMERCIAL AND INDUSTRIAL BUILDINGS
PURDUE UNIV., APRIL 12-14, (1976) 322-328
2.1.21
3.3.3

-KENT, HANDEGORD, ROBINSON (1966)
"A STUDY OF HUMIDITY VARIATIONS IN CANADIAN HOUSES"
ASHRAE TRANS. 1966; 72-II: II.1.1-II.1.8
4.2.2

-KRONVALL (1977)
"TESTING OF HOUSES FOR AIR-LEAKAGE USING A PRESSURE METHOD"
LUND INSTITUTE OF TECHNOLOGY, DIV. OF BUILD. TECH. 1977;
2.2.5
3.1.13.

-LAGUS (1977)
"CHARACTEIZATION OF BUILDING INFILTRATION BY THE TRACER
"DILUTION METHOD"
ENERGY 1977; 2: 461-464
3.5.8

-LASCHOBER, HEALY (1964)
"STATISTICAL ANALYSES OF AIR LEAKAGE IN SPLIT-LEVEL RESIDENCES"
ASHRAE TRANS. 1964; 70: 364-374
3.1.14
4.1.18
5.1.15
5.2.7
6.2.6

-LIDWELL (1960)
"THE EVALUATION OF VENTILATION"
J.HYG. 1960; 58: 297-305
2.1.22

-LOVELOCK (1963)
"ELECTRON ABSORPTION DETECTORS AND TECHNIQUE FOR USE IN
"QUANTITATIVE AND QUALITATIVE ANALYSIS BY GAS CHROMOTOGRAPHY"
ANAL. CHEM. 1963; 35: 474-481
2.1.23

-LUCK, NELSON (1977)
"THE VARIATION OF INFILTRATION RATE WITH RELATIVE
"HUMIDITY IN A FRAME BUILDING"
ASHRAE TRANS. 1977; 83-I:
2.1.25
3.1.15
4.1.19
4.2.3
5.1.16

-MALIK (1977)
"AIR INFILTRATION IN HOMES"
PRINCETON UNIV. CENTER FOR ENVIRONMENTAL STUDIES REPORT 58, SEPT. 1977
3.1.16
6.2.7

-MALINOWSKI (1971)
"WIND EFFECT ON THE AIR MOVEMENT INSIDE BUILDINGS"
PROCEEDINGS OF THE THIRD INTERNATIONAL CONFERENCE ON
WIND EFFECTS ON BUILDINGS AND STRUCTURES
TOKYO, 1971; 125-134
4.1.20

-MATTINGLY, PETERS (1975)
"WIND AND TREES--AIR INFILTRATION EFFECTS ON ENERGY IN
"HOUSING"
PRINCETON UNIV. CENTER FOR ENVIRONMENTAL STUDIES, REPORT #20. MAY 1975
2.3.5
4.1.21
5.5.2

-MIN (1958)
"WINTER INFILTRATION THROUGH SWINGING-DOOR ENTRANCES IN
"MULTI-STORY BUILDINGS"
ASHRAE TRANS. 1958; 64: 421-446
5.2.8

-OLSSON (1977)
"VENTILATION AND THE DRAUGHT-PROOFING OF WINDOWS IN OLD
"BLOCKS OF FLATS"
LUND INSTITUTE OF TECHNOLOGY:
DEPARTMENT OF BUILDING SCIENCE REPORT, 1977.
5.1.17

-PETTENKOFER (1858)
"UEBER DEN LUFTWECHSEL IN WOHNGEBAUDEN"
MUNICH, 1858
2.1.14

-SASAKI, WILSON (1965)
"AIR LEAKAGE VALUES FOR RESIDENTIAL WINDOWS"
ASHRAE TRANS. 1965; 71: 81-88
2.2.6
5.1.18

-SCHUTRUM, OZISIK, BAKER, HUMPHREYS (1961)
"AIR INFILTRATION THROUGH REVOLVING DOORS"
ASHRAE TRANS. 1961; 67: 488-506
2.2.7
5.2.9

-SEPSY, JONES, MCBRIDE, BLANCETT (1977)
"OSU/EPRI FINAL REPORT--CHAPTER 9, AIR INFILTRATION"
OSU/EPRI FINAL REPORT 1977; ENVIRONMENTAL CONTROL GROUP
DEPT. OF MECHANICAL ENGINEERING, COLUMBUS, OHIO 43210
2.1.26
3.1.17
5.1.19
6.2.8

-SHAW, SANDER, TAMURA (1973)
"AIR LEAKAGE MEASUREMENTS OF THE EXTERIOR WALLS OF TALL BUILDINGS"
ASHRAE TRANS. 1973; 79-II: 40-48
3.3.4

-SHAW, TAMURA (1977)
THE CALCULATION OF AIR INFILTRATION RATES CAUSED BY

WIND AND STACK ACTION FOR TALL BUILDINGS"
ASHRAE TRANS. 1977; 83-II=
2.3.6 "
3.4.11
6.1.8

-SHAW, WHYTE (1974)
"AIR MOVEMENT THROUGH DOORWAYS--THE INFLUENCE OF TEMPERATURE
"AND ITS CONTROL BY FORCED AIRFLOW"
BUILD. SERV. ENG. 1974; 42= 210-218
5.2.10

-SHELTON (1976)
"THE ENERGY COST OF HUMIDIFICATION"
ASHRAE J. 1976; 18= 52-55
4.2.4

-SINDEN (1976)
"THEORETICAL BASIS FOR TRACER GAS MEASUREMENTS OF
"AIR INFILTRATION"
PRINCETON UNIV; TWIN RIVERS PROJECT, NOTE 5, MARCH 1976
2.1.27

-SINDEN (1976)
"WIND, TEMPERATURE, AND NATURAL VENTILATION"
PRINCETON UNIV. TWIN RIVERS PROJECT -NOTE 6, JUNE 1976
4.1.22

-SMITH (1951)
"FEASIBILITY OF USING MODELS FOR PREDETERMINING NATURAL VENTILATION"
TEXAS A & M UNIV. 1951; RESEARCH REPORT #26
3.4.12

-SONDEREGGER (1977)
"DYNAMIC MODELS OF HOUSE HEATING BASED ON EQUIVALENT
"THERMAL PARAMETERS"
PH.D. DISSERTATION, PRINCETON UNIVERSITY, SEPT. 1977
4.1.23

-SPRENGER (1971) GERMAN
"EXPERIMENTELLE STROMUNGSUNTERSUCHUNGEN IM VERSUCHS-
"AUDITORIUM DER ETH ZURICH"
GESUND. ING. 1971; 92= 225-231
3.5.~~7~~8

-STRICKER (1975)
"MEASUREMENT OF AIR-TIGHTNESS OF HOUSES"
ASHRAE TRANS. 1975; 81= 148-167
2.2.8
3.1.18
4.2.5
5.4.8

-TAMURA (1969)
"COMPUTER ANALYSIS OF SMOKE MOVEMENT IN TALL BUILDINGS"
ASHRAE TRANS. 1969; 75= 81-92
3.4.13

-TAMURA (1970)
"ANALYSIS OF SMOKE SHAFTS FOR CONTROL OF SMOKE MOVEMENT IN
"BUILDINGS"
ASHRAE TRANS. 1970; 76= 290-297

3.3.5
3.4.14

-TAMURA (1975)
"MEASUREMENTS OF AIR LEAKAGE CHARACTERISTICS OF HOUSE
"ENCLOSURES"
ASHRAE TRANS. 1975; 81≡ 202-211
2.2.9
3.1.20
5.1.20
5.2.11

-TAMURA, SHAW (1976)
"STUDIES ON EXTERIOR WALL AIR TIGHTNESS AND AIR INFILTRATION
"OF TALL BUILDINGS"
ASHRAE TRANS. 1976; 82≡ 122-134
3.3.6

-TAMURA, WILSON (1964)
"AIR LEAKAGE AND PRESSURE MEASUREMENTS ON TWO OCCUPIED HOUSES"
ASHRAE TRANS. 1964; 70≡ 110-119
3.1.19
4.1.24
5.3.6

-TAMURA, WILSON (1966)
"PRESSURE DIFFERENCES FOR A NINE-STORY BUILDING AS A RESULT
"OF CHIMNEY EFFECT AND VENTILATION SYSTEM OPERATION"
ASHRAE TRANS. 1966; 72≡ 180-189
3.3.7

-TAMURA, WILSON (1967)
"PRESSURE DIFFERENCES CAUSED BY CHIMNEY EFFECT IN THREE
"HIGH BUILDINGS"
ASHRAE TRANS. 1967; 73≡ II.1.1-II.1.10
3.3.8

-TAMURA, WILSON (1967)
"BUILDING PRESSURES CAUSED BY CHIMNEY ACTION AND MECHANICAL
"VENTILATION"
ASHRAE TRANS. 1967; 73≡ II.2.1-II.2.12
3.4.15

-TAMURA, WILSON (1968)
"PRESSURE DIFFERENCE CAUSED BY WIND ON TWO TALL BUILDINGS"
ASHRAE TRANS. 1968; 74≡ 170-181
3.3.9

4.1.25
-TAMURA, WILSON (1970)
"NATURAL VENTING TO CONTROL SMOKE MOVEMENT IN BUILDING
"VIA VERTICAL SHAFTS"
ASHRAE TRANS. 1970; 76≡ 279-289
3.4.16

-TIPPING, HARRIS-BASS, NEVRALA (1974)
"VENTILATION--DESIGN CONSIDERATIONS"
BUILD. SERV. ENG. 1974; 42≡ 132-141
5.4.9

-TORRANCE (1972)
"WIND PROFILES OVER A SUBURBAN SITE AND WIND EFFECTS

"ON A HALF FULL-SCALE MODEL BUILDING"
BUILD._SCI. 1972; 7≡ 1-12
3.4.17
4.1.26
4.3.5

-TSUCHIYA (1976)
"NUMERICAL CALCULATION OF ROOM AIR MOVEMENT--ISOTHERMAL
"TURBULENT TWO DIMENSIONAL CASE--"
BUILDING RESEARCH INSTITUTE, TOKYO, PAPER #62, JAN. 1976
3.4.18

-WARREN (1977)
"VENTILATION THROUGH OPENINGS ON ONE WALL ONLY"
BUILDING RESEARCH ESTABLISHMENT REPORT, AUGUST 1977
4.1.27

-WARREN, WEBB (1976)
"AIR SUPPLY FOR DOMESTIC COMBUSTION APPLIANCES"
BUILD. ENVIRON. 1976; 11≡ 259-269
5.3.7.

-WEST (1977)
"CONTAMINANT DISPERSION AND DILUTION IN A VENTILATED SPACE"
ASHRAE TRANS. 1977; 83-I≡ 125-140
2.1.28
3.4.20

-WHITE (1954)
"EFFECTS OF LANDSCAPE DEVELOPMENT ON THE NATURAL VENTILATION
"OF BUILDINGS"
TEXAS A ^ M UNIV. 1954; RESEARCH REPORT #45
3.4.19

-WILSON (1961)
"INFLUENCE OF THE HOUSE ON CHIMNEY DESIGN"
ASHRAE TRANS. 1961; 67≡ 317-329
5.4.10

LITERATURE SURVEY REPORT
AN ANNOTATED BIBLIOGRAPHY ON AIR INFILTRATION IN BUILDINGS
PREPARED BY R.C. DIAMOND AND D.T. GRIMSRUD
LAWRENCE BERKELEY LABORATORY, JANUARY 1978

STRUCTURE

1.0 REVIEW ARTICLES

1.0.1
"INFILTRATION AND NATURAL VENTILATION" CHAPTER 21
-ASHRAE HANDBOOK OF FUNDAMENTALS (1977)
THE STANDARD REFERENCE FOR NORTH AMERICAN ARCHITECTS AND ENGINEERS, WITH EXTENSIVE BIBLIOGRAPHY.

1.0.2
"REVIEW OF EXPERIMENTAL TECHNIQUES FOR THE INVESTIGATION OF NATURAL VENTILATION IN BUILDINGS"
-HITCHEN, WILSON (1967)
REVIEWS TRACER GAS TECHNIQUES, MEASUREMENTS OF LOW AIRSPEEDS, AND THE USE OF MODELS IN VENTILATION STUDIES.
BUILD. SCI. 1967; 2: 59-82

1.0.3
"AIR INFILTRATION" SECTION A4
-IHVE GUIDE BOOK A (1970)
STANDARD BRITISH REFERENCE ON AIR INFILTRATION.

1.0.4
"VENTILATION THEORY AND PRACTICE"
-JENNINGS, ARMSTRONG (1971)

APPENDIX B

COMMERCIAL BUILDING MODELS

No. 2459

THE CALCULATION OF AIR INFILTRATION RATES CAUSED BY WIND AND STACK ACTION FOR TALL BUILDINGS

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The air that leaks through cracks and openings in a building envelope contributes to the heating and cooling loads of a building. Because its contribution to the total loads can be quite large, accurate estimates of infiltration rates are required for proper sizing of HVAC systems and analyzing the performance of various energy conservation measures. At present, methods for calculating infiltration rates are either over simplified with possible attendant large errors or very complicated involving the use of a computer model building.

A method for calculating the air infiltration rate caused by stack action was given in a previous ASHRAE paper[1] by the authors. For this paper, it was necessary to develop methods for calculating infiltration rates caused by wind action alone and in combination with stack action. A literature search for suitable wind pressures measurements for air infiltration calculations revealed that investigations of wind pressures on tall buildings have been directed almost exclusively to improving structural load calculations with measurements concentrated on those areas of the wall surfaces likely to be exposed to the greatest wind pressures. As air can leak through any part of exterior walls, detailed information on the distribution of wind pressures is required for infiltration calculation.

Recently, the National Aeronautical Establishment of the National Research Council of Canada (NRCC) conducted extensive pressure measurements on a tall building model in a boundary layer wind tunnel. Wind pressure data from this investigation were made available to the authors and, with the aid of a computer model building, procedures for calculating air infiltration rates were developed.

WIND TUNNEL PRESSURE MEASUREMENTS

Wind pressures on the surfaces of a plexiglass model representing a building 100 ft (31 m) by 150 ft (46 m) and 600 ft (183 m) high at a 1:400 scale, were measured in the 6 ft (1.83 m) by 9 ft (2.74 m) NRCC wind tunnel. The pressure taps on the model were distributed horizontally at the one-third and two-third heights for the four walls and vertically along the centerline of two adjacent walls (Fig. 1).

The wind velocity profile for a full suburban boundary layer was simulated according to the following equation:[2]

$$V_z = KZ^{1/3} \tag{1}$$

where V_z is the velocity at height Z above ground and K is constant. The velocity profile was developed in the tunnel using an upstream array of spires. No blocks were used to simulate ground roughness.

The model was placed on the turntable of the working section and was rotated 180 deg with a set of pressure readings taken at each 15-deg increment. They were converted to pressure

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coefficients related to the wind velocity at the roof level using the following equation

$$C_{pz} = \frac{P_z}{P_{vt}} \quad (2)$$

where

C_{pz} = pressure coefficient at height Z
P_z = pressure at height Z referenced to that of the free air stream
P_{vt} = velocity pressure at roof level

The distribution of wind pressure coefficients for the two horizontal levels for wind angles of 0 and 45 deg with respect to the normal on the long side surface are given in Fig. 2. It shows that they are less than unity and that they vary on the windward wall and are almost constant on the side and leeward walls.

Factors relating the mean and the centerline pressure coefficients were calculated for the two levels and applied to the centerline pressure coefficients for other levels to obtain the vertical distribution of mean pressure coefficients for various wind angles shown in Fig. 3. These values were applied to the computer model building to develop procedures for air infiltration calculations. It was assumed that the pressure coefficients can be applied to buildings with width to length ratio of 1:1 to 1:2 (wind tunnel model was 1:1.5) and to buildings of any height.

COMPUTER MODEL BUILDING

Pressures imposed by wind and temperature difference forces are distributed inside a building in such a way that for steady state, air inflow and outflow for individual compartments are always equal. Hence, for a given outside condition, the patterns of pressure difference and air leakage depend on the flow resistances of all the separations. Modeling a building requires assigning values of flow resistances to the separations.

An open floor office building 100 ft (31 m) by 150 ft (46 m) and a floor height of 10 ft (3 m) was used as a basic model as shown in Fig. 4. The major separations of the model are the exterior walls, walls of vertical shafts and floors. The leakage areas in the major separations for each story were lumped and represented by flow coefficients (see Fig. 4) which were based on the average values obtained from tests conducted on several tall buildings by the authors[1,3]

The flow of air through a leakage opening can be represented by

$$Q = C\,(\Delta P)^n \quad (3)$$

where

Q = air leakage rate, cfm (m^3/s)
C = flow coefficient, cfm/in. of $water^n$ ($m^3/s\ Pa^n$)
ΔP = pressure difference, in. of water (Pa)

A flow balance equation can be set up for each compartment in the model using Eq. 3. Given the values of outside pressures, all inside pressures can be solved by iterative calculations; hence, pressure difference and air leakage rate for all separations can be calculated. The mathematical model and the computer program used for this paper are given in Ref 4.

RESULTS AND DISCUSSIONS

Computer calculations were conducted for building heights of 10, 20, 30 and 40 stories and width to length ratios of 1:1, 1:1.5 and 1:2 for wind acting directly on the long wall. The effect of changing the wind angles were investigated on the 20-storey model.

Air Infiltration Caused by Wind

Pressure differences across the exterior walls obtained from the computer results were nondimensionalized by dividing them by the wind velocity pressure at the roof level. For the purpose of this paper, they are referred to as pressure difference coefficient (C_p'). The vertical distribution of pressure difference coefficients for the four walls for wind angles [illegible]

Fig. 3 are also shown as dashed lines in Fig. 5. For wind angle of 0 deg (normal to the long wall) the C_p' curves are shifted to the right with values of C_p' greater than C_p for the windward wall and less for the leeward and side walls. For wind angle of 45 deg the values of C_p' and C_p are almost identical. The values of C_p' relative to those of C_p vary with wind direction as the former are referenced to the inside pressures which adjust to maintain a balance of air inflow and outflow.

At any level, the sum of the absolute values of C_p' of the windward and leeward or windward and side walls were about equal to those of C_p. Also, air flow inside the model building was mainly from the windward to the leeward and side walls with less than 5% of the total infiltration rate in the vertical direction from the central portion of the building to the upper and lower floors. It would appear that each floor behaved independently and can be treated separately when considering infiltration caused by wind action alone.

Fig. 6 shows the pressure differences across the four walls with changes in wind direction for the model building with width to length ratio of 1:1.5. They are expressed as the ratio of the pressure difference across the exterior wall over that of the long wall with wind acting normal to that wall (Side 1). The ratios can be estimated from the following equations obtained by curve fitting.

Side 1
$$\frac{\Delta P_{\theta,1}}{\Delta P_{o,1}} = -0.013\theta + 1.0 \tag{4}$$

Side 2
$$\frac{\Delta P_{\theta,2}}{\Delta P_{o,1}} = 0.0165\theta - 0.4 \tag{5}$$

Side 3
$$\frac{\Delta P_{\theta,3}}{\Delta P_{o,1}} = \begin{cases} -0.005\theta - 0.14 & \text{for } 0 \leq \theta \leq 45 \\ 0.003\theta - 0.5 & \text{for } 45 \leq \theta \leq 90 \end{cases} \tag{6}$$

Side 4
$$\frac{\Delta P_{\theta,4}}{\Delta P_{o,1}} = e^{(0.068\theta - 6.914)} - 0.388 \tag{7}$$

<u>where</u>

θ = wind angle measured counter clockwise from normal of Side 1, deg

$\Delta P_{o,1}$ = pressure difference across wall of Side 1 with θ = 0 deg

$\Delta P_{\theta,1}$, $\Delta P_{\theta,2}$, $\Delta P_{\theta,3}$, $\Delta P_{\theta,4}$ = pressure differences across walls of Sides 1, 2, 3, and 4 for wind angle = θ

The pressure difference across the long wall (Side 1) is maximum when θ = 0 deg and decreases linearly with wind direction to zero at θ = 75 deg. The pressure difference across the short wall (Side 2) is zero at θ = 25 deg and increases linearly to a maximum value at θ = 90 deg. Thus, as the wind angle changes from 0 to 90 deg, air infiltrates through the long wall from 0 to 25 deg, both the long and short walls from 25 to 75 deg and the short wall from 75 to 90 deg.

Fig. 7 shows the variation in infiltration rate with changes in wind angle and expressed as a ratio Q_θ/Q_o where Q_θ is the infiltration rate for a given wind angle θ and Q_o is the long side infiltration rate with θ = 0 deg. They are given for width to length ratios of 1:1, 1:1.5 and 1:2. Infiltration rates for any wind angle can be estimated from this figure knowing the infiltration rate of the long wall with θ = 0 deg. It is seen that the maximum infiltration rate occurs when the wind direction is normal to the long wall.

Fig. 5 shows that the pressure difference coefficient, C_p', varies with height above ground. To simplify calculation of infiltration and exfiltration rates with wind acting normal to the long wall, mean pressure difference coefficients, C_{pm}', were calculated by solving for pressure difference, ΔP, in Eq 3 using the total infiltration rates obtained from the computer model results. The values are 0.96, - 0.13 and - 0.38 for the windward, leeward and side walls respectively.

The values of C_p and C'_p discussed so far are related to the wind speed at the roof level. They can be expressed in terms of the meteorological wind speed by using the following equation:

$$\frac{V_t}{V_s} = \left(\frac{G_s}{Z_s}\right)^{1/7} \left(\frac{H}{G}\right)^{1/3} \qquad (8)$$

<u>where</u>

- V_t = mean wind speed at top of building, mph (m/s)
- Z_s = anemometer height at the meteorological station, ft (m)
- V_s = mean wind speed at height Z_s at the meteorological station, mph (m/s)
- G_s = gradient height at the meteorological station, ft (m)
- H = height of building, ft (m)
- G = gradient height at building site, ft (m)

Letting Z_s, G_s and G be 32 ft (10 m), 900 ft (274 m) and 1500 ft (457 m) respectively[2] the ratio of V_t/V_s is given by the following equation:

$$\frac{V_t}{V_s} = 0.142\ H^{1/3} \qquad (9)$$

Note: When SI units are used, constant 0.142 in Eq 9 is replaced by 0.211.

With $C'_{pm} = \dfrac{\Delta P_m}{\frac{1}{2}\rho V c^2}$ and using Eq 9, the mean pressure difference equation with wind acting normal to the wall was developed:

$$\Delta P_m = B\ H^{2/3}\ V_s^2 \qquad (10)$$

<u>where</u>

- ΔP_m = mean pressure difference, in of water (Pa)
- B = $1.30 \times 10^{-4}\ \rho\ C'_{pm}$ (The values of C'_{pm} are given above; ρ = air density, lb/ft^3.)

The values of B assuming ρ = 0.075 lb/ft^3 are as follows:

	B	(SI Unit)
windward wall	9.33×10^{-6}	(0.0256)
leeward wall	-1.27×10^{-6}	(-0.0035)
side walls	-3.64×10^{-6}	(-0.0100)

The infiltration rate for a given wall can be calculated by

$$Q = C_w\ A\ (\Delta P)^{0.65} \qquad (11)$$

<u>where</u>

- Q = infiltration rate, cfm (m^3/s)
- A = wall area, sq ft (m^2)
- C_w = flow coefficient, cfm/sq ft/(in. of water)$^{0.65}$ (m^3/s/m^2 Pa$^{0.65}$)

By substituting ΔP_m of Eq 10 for ΔP in Eq 11 and applying a factor a for wind direction, the infiltration equation is as follows:

$$Q_w = 5.375 \times 10^{-4}\ \alpha C_w\ LH^{1.435}\ V_s^{1.30} \qquad (12)$$

where

Q_w = infiltration rate caused by wind, cfm (m^3/s)

α = Q_θ/Q_o (values from Fig. 7 for various wind angles)

C_w = flow coefficient, cfm/sq ft/(in. of water)$^{0.65}$ ($m^3/s/m^2\ Pa^{0.65}$)

L = length of wall, ft (m)

H = building height, ft (m)

V_s = wind speed at weather station, mph (m/s)

Note: When SI units are used, replace constant 5.375×10^{-4} in Eq 12 by 0.0925.

Maximum infiltration rate occurs when wind is acting directly on the long wall with α = 1.0.

Suggested values of C_w for curtain wall construction with sealed windows are as follows[1]

	C_w	(SI Unit)
Tight wall	0.22	0.31×10^{-4}
Average wall	0.66	0.93×10^{-4}
Loose wall	1.30	1.83×10^{-4}
Masonry wall*	4.00	5.63×10^{-4}

* Measurement on one masonry wall building[6]

The selection of the air tightness value for a curtain wall depends mainly on the joint design and workmanship during building construction. Air leakage tests on several buildings indicated that the exterior walls constructed with close supervision of workmanship can be expected to have low leakage rates.[1]

Example 1

Calculate total infiltration rate caused by 20 mph (8.94 m/s) wind measured at a weather station with wind acting directly on the long wall of a building 100 ft (31 m) by 150 ft (46 m) and 200 ft (61 m) high. The air leakage value of the exterior wall is C_w = 0.66 (0.93×10^{-4}). The building is located in a suburban terrain.

From Eq 12

$$Q_w = 5.375 \times 10^{-4} \times 1.0 \times 0.66 \times 150 \times (200)^{1.435} \times (20)^{1.30}$$
$$= 5240 \text{ cfm } (2.47\ m^3/s)$$

The corresponding leakage rate obtained from the full computer model was 5356 cfm.

The infiltration rate for other than wind acting normal to the long wall can be calculated using values of α in Fig. 7. For example, with wind angle of θ = 45 deg the value of α for width to length ratio of 1:1.5 is 0.88.

Therefore

$$Q_w = 0.88 \times 5240 = 4611 \text{ cfm } (2.18\ m^3/s)$$

4690 cfm (computer result)

Nearby structures can affect wind pressures around a building. To investigate this effect on infiltration rate, wind pressure coefficients given by Bailey and Vincent[5] were applied to the computer model building. Results indicated that with the height of the shielding building of one-third, two-thirds and equal to the height of the shielded building and the distance between the buildings within 3 times the building width, the infiltration rate of the fully exposed building was reduced by 0, 20 and 60% respectively.

Air Infiltration Caused by Stack Action

The general equation for calculating infiltration rate caused by stack action was given in a previous ASHRAE paper by the authors(1)

$$Q_s = C_w S \left[0.52\ Y\ p \left(\frac{\Delta T}{T_i T_o}\right)\right]^n \frac{(\beta H)^{n_w+1}}{n_w+1} \quad (13)$$

where

- Q_s = total infiltration rate caused by stack action, cfm (m^3/s)
- C_w = exterior wall flow coefficient, cfm/ft^2 of wall area (in. of water)^n ($m^3/s/m^2 Pa^n$)
- S = perimeter of the building, ft (m)
- Y = ratio of actual to theoretical pressure difference (thermal draft coefficient)
- p = atmospheric pressure, lb/in.^{2} (Pa)
- T_o = absolute temperature outside, R(K)
- T_i = absolute temperature inside, R(K)
- ΔT = inside-outside temperature difference, $T_i - T_o$, R (K)
- n_w = flow exponent
- β = ratio of height of neutral pressure level above ground to building height

Note - When SI units are used, constant 0.52 in Eq 12 is replaced by 0.0342.

The thermal draft coefficient, Y, depends on the air tightness of the exterior walls relative to that of the interior construction. With the interior completely open, the value Y is one, whereas with each story completely sealed from others, it is zero. Measured values Y on a few buildings[7] indicate that 0.80 may be used for office buildings. Measured values of Y for apartment buildings are not available. They will probably be lower than those of office buildings because of looser exterior wall construction and tighter interior construction with compartmentation of floor spaces and fewer elevator and service shafts. Assuming a value of Y for office buildings would give a conservative estimate of infiltration rates for apartment buildings.

Eq 13 can be simplified for practical purposes by assuming the following: p = 14.7 psia (101.3 KPa) T_i = 530 R (294 K), n_w = 0.65 and β = 0.50 (neutral pressure level at mid-height). Substituting these values in Eq 13 gives

$$Q_s = 0.0113\ C_w\ S \left(Y\frac{\Delta T}{T_o}\right)^{0.65} H^{1.65} \quad (14)$$

Note - When SI units are used, constant 0.0113 in Eq 13 is replaced by 0.883.

Example 2

Calculate infiltration rate caused by stack action for the same building as in Example 1 with outside temperature of 0 F (-18 C), inside temperature of 75 F (24 C), no wind and Y = 1 (about the same as for the computer model).

From Eq 14,

$$Q_s = 0.0113 \times 0.66 \times 500 \left(1 \times \frac{75}{460}\right)^{0.65} (200)^{1.65} = 7180 \text{ cfm } (3.39\ m^3/s)$$

7670 cfm (computer result)

Infiltration rates caused by wind action alone (wind normal to the long wall) and stack action alone for various wind speeds, inside-outside temperature differences and building heights are given in Fig. 8. They are expressed in cfm/sq ft of long wall area. The graph is based on C_w = 0.66 (9.3×10^{-4}) and Y = 1. For other values of C_w, the infiltration rates for wind and stack actions in Fig. 8 should be adjusted in direct proportion. For other values of Y, the infiltration rate for stack action should be adjusted by multiplying it by $Y^{0.65}$. For wind angle other than normal to the long wall, the infiltration rate for wind action should be

The graph was constructed to permit direct comparison of infiltration rates caused by wind and stack action. They are both expressed in cfm/sq ft of long wall area (Side 1 in Fig. 8). To account for the variation in width to length ratio when considering stack action, the infiltration rates are plotted against an adjusted inside-outside temperature difference using the following equation which was deduced from Eq 13.

$$\Delta T_a = \left(\frac{1 + w/\ell}{1.67} \right)^{1.54} \Delta T \tag{15}$$

where

ΔT_a = adjusted inside-outside temperature difference

ΔT = inside-outside temperature difference

w = width

ℓ = length

From Eq 15, ΔT_a equals ΔT for width to length ratio of 1:1.5.

In Fig. 8, any point on a constant building height line will give the wind velocity and ΔT_a required to produce equal infiltration rates. For example, for a building height of 200 ft (61 m), the infiltration rate caused by ΔT_a of 45 F (25 C) is equal to that caused by wind of 20 mph (8.94 m/s) as given by Point 1 of Fig. 8.

Air Infiltration Caused by the Combined Action of Wind and Stack Action

The computer results indicated that the air infiltration rates caused by stack action alone, Q_s, and wind action alone, Q_w, cannot be added to obtain the infiltration rate caused by the combination of both actions, Q_{ws}.

An equation was developed to calculate Q_{ws},

$$\frac{Q_{ws}}{Q_{lrg}} = 1 + 0.24 \left(\frac{Q_{sml}}{Q_{lrg}} \right)^{3.3} \tag{16}$$

where

Q_{ws} = infiltration rate caused by combined wind and stack action

Q_{lrg} = larger value of Q_w and Q_s

Q_{sml} = smaller value of Q_w and Q_s

The two ratios in Eq 16 are plotted on Fig. 9. It shows that Q_{ws} is about equal to the infiltration rate caused by the larger of the two motive forces. When Q_w equals Q_s, Q_{sw} is 24% greater than either Q_w or Q_s.

Example 3

Calculate infiltration rate caused by both wind and stack action for the same building as in Examples 1 and 2 for wind speed of 20 mph (8.94 m/s), outside temperature of 0 F (-18 C) and inside temperature of 75 F (24 C).

From the results of Examples 1 and 2,

Q_w = 5240 cfm (2.45 m^3/s)

Q_s = 7180 cfm (3.39 m^3/s)

Since Q_s is larger than Q_w, from Eq 16,

$$\frac{Q_{sml}}{Q_{lrg}} = \frac{5240}{7180} = 0.730$$

$$\frac{Q_{ws}}{Q_{lrg}} = 1 + 0.24\ (0.730)^{3.3} = 1.085$$
(also from Fig. 9)

$$Q_{ws} = 7180 \times 1.085$$
$$= 7790 \text{ cfm } (3.67\ m^3/s)$$
8253 cfm (computer result)

The calculation of infiltration rates on a floor-by-floor or zone-by-zone basis would require a different approach than the one for overall infiltration rate. The computer results indicated that the pressure difference across the exterior wall at any level can be approximated by the algebraic sum of the pressure differences caused by wind and stack action.

$$\Delta P_{ws} = \Delta P_w + \Delta P_s \qquad (17)$$

where

ΔP_{ws} = pressure difference caused by wind and stack action

ΔP_w = pressure difference caused by wind action

ΔP_s = pressure difference caused by stack action

Although the pressure difference caused by the building air handling system was not included in this study, it likely can be added to the right hand side of Eq 17.

The pressure difference caused by stack action at any level is given by

$$\Delta P_s = 0.52\ \gamma\ p\ h \left(\frac{\Delta T}{T_i T_o}\right) \qquad (18)$$

where

h = distance from neutral pressure level, ft (m)

Note - When SI units are used constant 0.52 in Eq 18 is replaced by 0.0342.

Replacing h by (β-N) H in Eq 18,

where

N = ratio of height of level above ground to building height

$$\Delta P_s = 0.52\ \gamma\ p\ (\beta-N)\ H \left(\frac{\Delta T}{T_i T_o}\right) \qquad (19)$$

Assuming p = 14.7 psia (101.3 KPa),

β = 0.5 (neutral pressure level at mid-height)

and T_i = 530 R (294 K),

Eq 19 becomes

$$\Delta P_s = 0.0143\ \gamma\ (0.5-N)\ H \left(\frac{\Delta T}{T_o}\right) \qquad (20)$$

Note - When SI units are used constant 0.0143 in Eq 20 is replaced by 11.68.

For wind acting normal to the long wall, equations for pressure difference caused by wind were developed from pressure difference coefficient, C_p', given in Fig. 5. They are as follows:

Windward Wall

from N = 0 to 0.7

$\Delta P_w = (0.72 \text{ to } 0.48\ N)\ H^{2/3}\ V_s^2 \times 10^{-5}$ (21)

Note - When SI units are used replace constant 10^{-5} by 0.0275

from N - 0.7 to 1.0

$\Delta P_w = 1.05\ H^{2/3}\ V_s^2 \times 10^{-5}$ (22)

Note - When SI units are used replace constant 1.05×10^{-5} by 0.0289

Leeward Wall

$\Delta P_w = -1.27\ H^{2/3}\ V_s^2 \times 10^{-6}$ (23)

Note - When SI units are used replace constant 1.27×10^{-6} by 0.0035.

Side Wall

$\Delta P_w = -3.64\ H^{2/3}\ V_s^2 \times 10^{-6}$ (24)

Note - When SI units are used replace constant 3.64×10^{-6} by 0.010

F wind angles other than normal to the long wall apply factors from Eq 4, 5, 6 and 7 or Fig. 6 to pressure differences obtained from Eq 21.

Example 4

Calculate infiltration rates on the 5th floor of a 20-story building 100 ft (31 m) by 150 ft (46 m) and floor height of 10 ft (3.05 m) caused by a 20 mph (8.94 m/s) wind acting directly on the long wall and outside temperature of 0 F (-18 C) and inside temperature of 75 F (24 C). $\Upsilon = 1$; $C_w = 0.66\ (0.93 \times 10^{-4})$.

$\Delta P_s = 0.0143 \times 1\ (0.5 - \frac{5}{20})\ \ 200\ (\frac{75}{460})$ (20)

= 0.116 in. of water (29.0 Pa)

0.123 in. of water (computer result)

Windward Wall

$\Delta P_w = (0.72 + 0.48 \times \frac{5}{20})\ \ 200^{2/3}\ 20^2 \times 10^{-5}$ (21)

= 0.115 in. of water (28.6 Pa)

0.116 in. of water (computer result)

$\Delta P_{ws} = 0.115 + 0.116$ (17)

= 0.231 in. of water (57.5 Pa)

0.223 in. of water (computer result)

$Q_{ws} = 0.66 \times 10 \times 150\ (0.231)^{0.65}$ (11)

= 382 cfm ($0.18\ m^3/s$)

378 cfm (computer result)

Leeward Wall

$\Delta P_w = -1.27 \times 200^{2/3}\ 20^2 \times 10^{-6}$ (23)

= -0.017 in. of water (4.32 Pa)

-0.015 in. of water (computer result)

$\Delta P_{ws} = -0.017 + 0.116$ (17)

= 0.099 in. of water (24.6 Pa)

0.093 in. of water (computer result)

$$Q_{ws} = 0.66 \times 10 \times 150\ (0.099)^{0.65} \qquad (11)$$

= 220 cfm (0.17 m^3/s)

214 cfm (computer result)

Side Walls

$$\Delta P_w = -3.64 \times 200^{2/3}\ 20^2 \times 10^{-6} \qquad (24)$$

= -0.050 in. of water (12.4 Pa) ← ?

-0.049 in. of water (computer result)

$$\Delta P_{ws} = -0.050 + 0.116 \qquad (17)$$

= 0.066 in. of water (16.4 Pa)

0.059 in. of water (computer result)

$$Q_{ws} = 0.66 \times 10 \times 100\ (0.066)^{0.65} \qquad (11)$$

= 113 cfm (0.10 m^3/s)

106 cfm (computer result)

The total infiltration for the 5th floor is 382 + 214 + 2 x 106 = 808 cfm (0.38 m^3/s). Computer result is 804 cfm.

SUMMARY

By applying the pressure data obtained from a wind tunnel model study to a computer model building, a simple procedure for calculating exterior wall pressure differences and air filtration rates for various wind velocities and direction was developed. The wind tunnel essure data were assumed to apply to buildings of any height and width to length ratio of 1:1 to 1:2. Although they were obtained for a building in a suburban terrain, these data would apply to most buildings except those in a large city center. A limited study on the effect of nearby buildings indicated that infiltration rates can be reduced by as much as 60% of those for a fully exposed building.

Procedures for calculating infiltration rates caused by the combined action of wind and temperature difference forces were developed for the total building or for individual floors or zones. This study has indicated that the overall infiltration rate is governed by the larger of the two motive forces and that the exterior wall pressure differences at any level caused by wind and stack action are additive.

Procedures for infiltration calculations which are illustrated by examples can be used for proper sizing of HVAC systems and for energy load analysis on an hour by hour basis. The results obtained by using the procedures given in this paper can be expected to be in good agreement with those obtained from the use of a computer model building.

REFERENCES

1. Tamura, G.T. and Shaw, C.Y., "Studies on Exterior Wall Air Tightness and Air Infiltration of Tall Buildings," ASHRAE Transactions, Vol. 82, Part I, 1976.

2. Davenport, A.G., Wind Loads on Structures, Nat. Res. Council of Canada, Div. Bldg. Res. Tech. Paper 88, March 1960 (NRC 5576).

3. Tamura, G.T. and Shaw, C.Y., "Air Leakage Data for the Design of Elevator and Stairshaft Pressurization Systems", ASHRAE Transactions, Vol. 82, Part II, 1976.

Sander, D.M., "Fortran IV Program to Calculate Air Infiltration in Buildings," Nat. Res. Council of Canada, Div. Bldg. Res., Computer Program No. 37, May 1974.

5. Bailey, A. and Vincent, N.D.G., "Wind Pressure on Buildings Including Effects of Adjacent Buildings," Journal of the Institute of Civil Engineering, Vol. 19-20, No. 1, November 1942.

6. Tamura, G.T. and Wilson, A.G., "Pressure Differences for a 9-Story Building as a Result of Chimney Effect and Ventilation [illegible]

7. Tamura, G.T. and Wilson, A.G., "Pressure Differences Caused by Chimney Effect in Three High Buildings," ASHRAE Transactions, Vol. 73, Part II, 1967.

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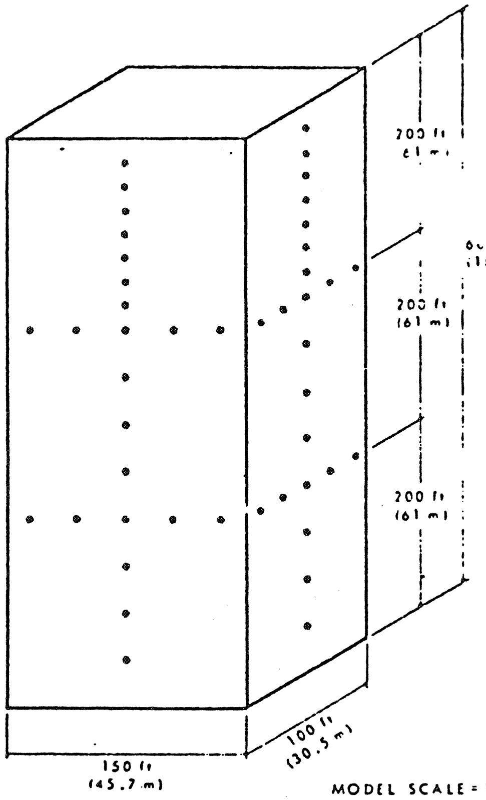

Fig. 1 Location of pressure taps on wind tunnel model

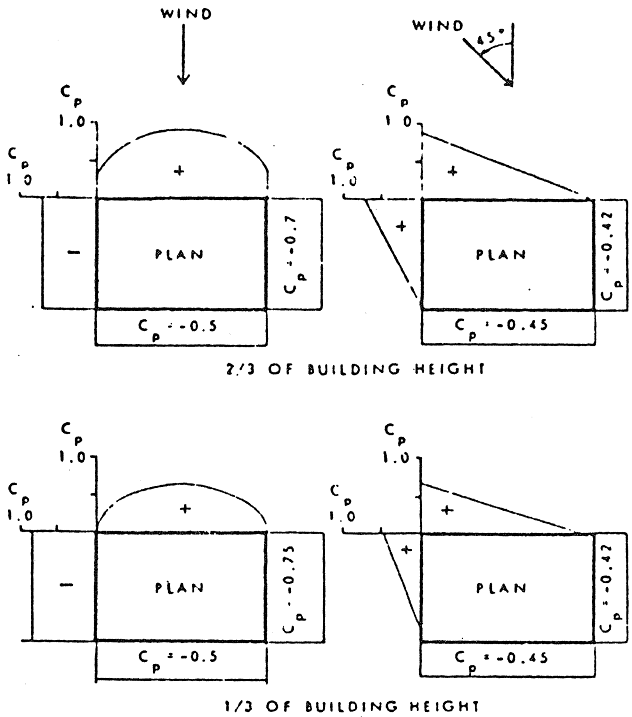

Fig. 2 Horizontal distribution of wind pressure coefficients, C_p

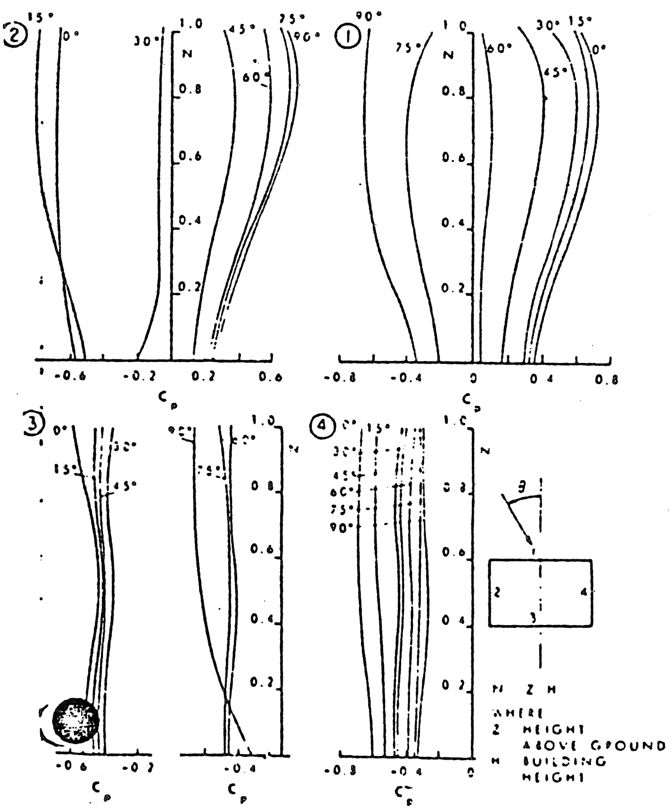

Fig. 3 Vertical distributions of mean wind pressure coefficient, C_p

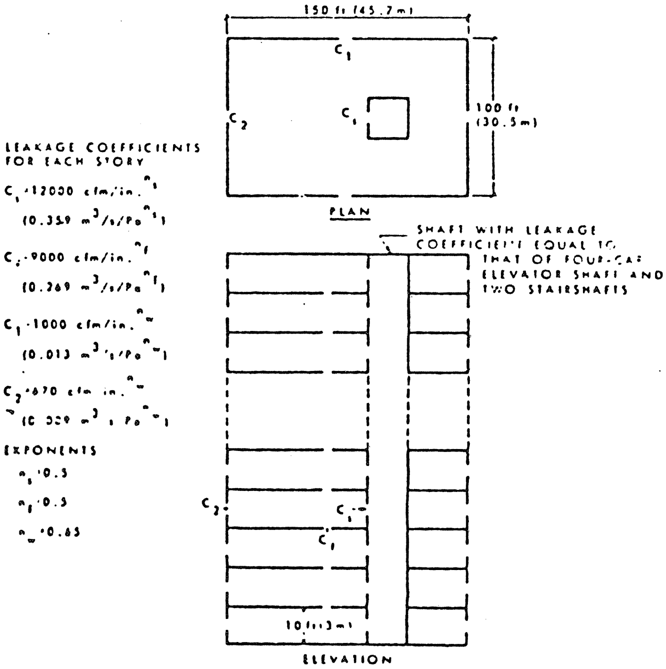

Fig. 4 Computer building model

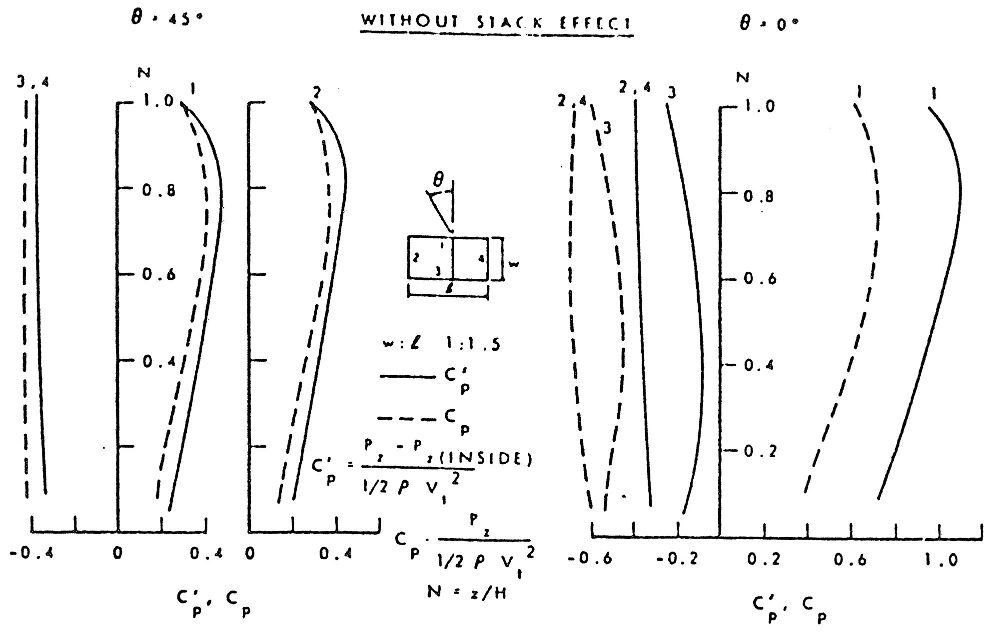

Fig. 5 Pressure difference coefficient, C'_p, and wind pressure coefficient, C_p' vs height

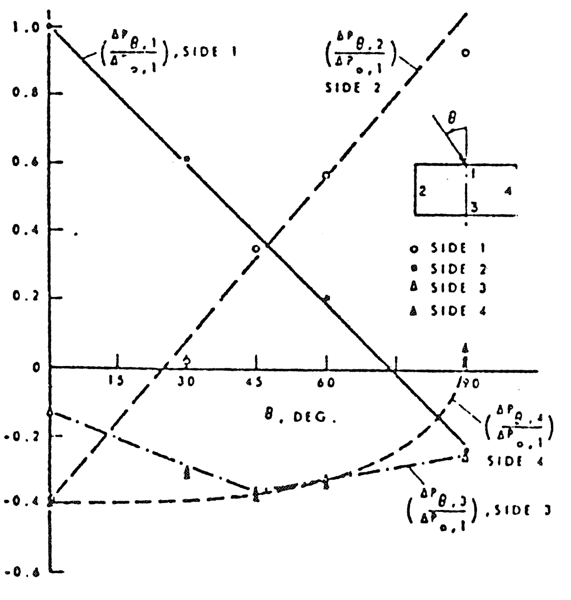

Fig. 6 Effect of wind direction on the mean pressure differences across exterior walls

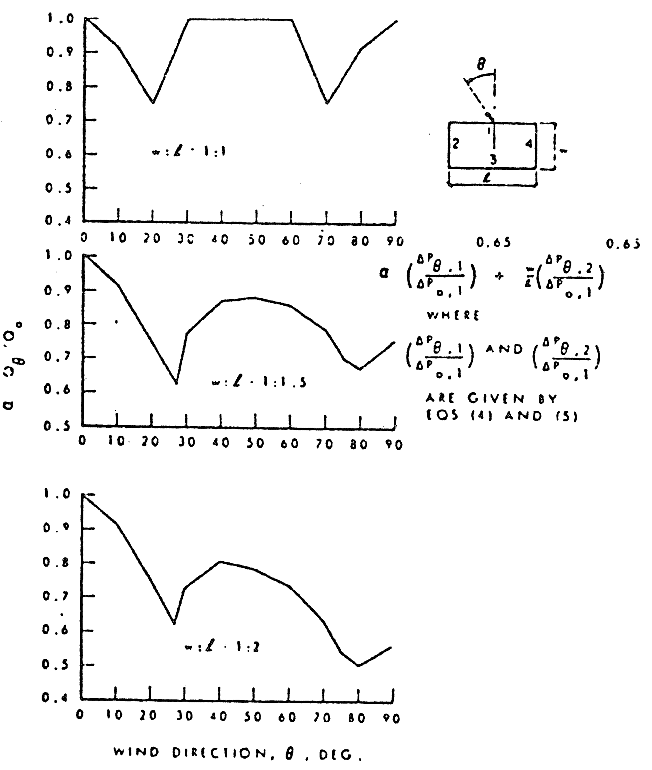

Fig. 7 Correction factor of air infiltration rate due to wind approaching at various directions

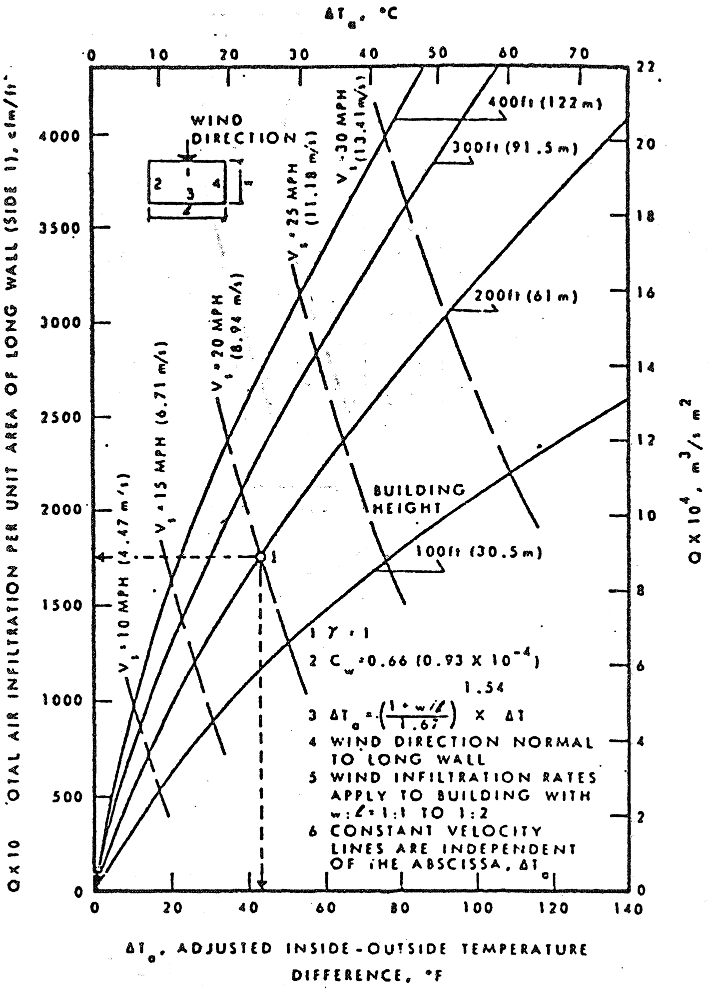

Fig. 8 Air infiltration rates caused : either by wind or stack action

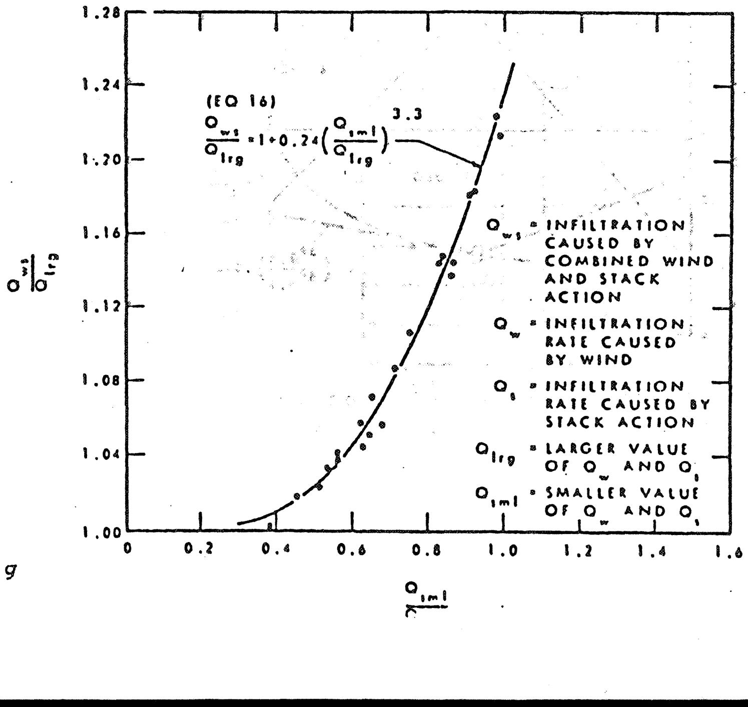

Fig. 9 Factors for determining infiltration rates caused by combined wind and stack action.

No. 2488

STUDIES ON EXTERIOR WALL AIR TIGHTNESS AND AIR INFILTRATION OF TALL BUILDINGS

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One of the functions of the exterior walls of buildings is to separate outdoor elements from the inside environment. Building envelopes are not normally completely air tight and they permit some flow of air into and out of them through joints and cracks in the wall fabric. This leakage of air contributes to heating and cooling loads and must be taken into account in any energy analysis of buildings and design of HVAC systems.

Infiltration rates depend primarily on the air leakage characteristics of exterior walls and to a lesser extent on those of interior separations such as floor construction, interior partitions and various service shafts. A reliable prediction of the infiltration rates of multi-storey buildings is hampered, at present, by the scarcity of information on the actual air leakage characteristics of exterior walls.

The National Research Council of Canada has taken measurements of the air leakage characteristics of the exterior walls of eight multi-storey office buildings located in Ottawa, Canada. Varying in height from 11 to 22 stories, with curtain wall construction and fixed glazing, they were built during the sixties and early seventies. The results of the measurements are reported in this paper. A method for calculating infiltration rates caused by stack action has been developed and is applied to heat loss calculations using the measured wall leakage values.

EXTERIOR WALL MEASUREMENTS

The results of air leakage measurements of the exterior walls of four multi-storey buildings were reported by Shaw, Sander and Tamura.[1] This project was subsequently expanded to include four additional buildings, using the same test method (Table 1). Briefly, it involved pressurizing all typical floor spaces between the ground floor and the top mechanical floor, using 100% outside air for the central supply air systems with return and exhaust systems shut down. Supply air rates were varied and the concomitant pressure differences across the pressurized enclosure recorded. To ensure stable pressure differences across the building enclosure, the tests were conducted during unoccupied periods and when there was little or no wind.

Under steady-state condition the rate of supply of outside air equals the sum of the air leakage rates through the exterior walls of typical floors, bottom and top separations (Fig. 1). It can be expressed as follows:

$$Q_s = C_w \sum_{j=1}^{N} (A_w \Delta P_w^{\,n_w})_j + C_b A_b (\Delta P_b)^{n_b} + C_t A_t (\Delta P_t)^{n_t} \qquad (1)$$

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where

Q_s total outdoor air supply rate, cfm

n flow exponent

C flow coefficient, cfm/(sq ft)(in. of water)^n

ΔP = pressure difference, $P_i - P_o$, in. of water

P_i = inside pressure, in. of water

P_o = outside pressure, in. of water

A = area, sq ft

N = total number of floors with typical wall construction

subscripts

w = exterior wall

b = bottom separation

t = top separation

The values of Q_s, ΔP_w, ΔP_b and ΔP_t can be measured. By obtaining several sets of these values it is possible to determine the values of flow coefficients C_w, C_b and C_t and the flow exponents n_w, n_b and n_t, defining air leakage characteristics of the three separations. Details of test methods and data analysis are given in Ref 1.

TEST RESULTS

The values of flow coefficient and exponent, as defined in Eq 1 for the eight test buildings, are given in Table 2. Using these values, the over-all air leakage rates in terms of cfm per sq ft of outside wall area vs pressure difference were plotted on Fig. 2. These values, which include the air leakage rates through the top and bottom as well as through the exterior walls, are useful in estimating the supply air rates required for pressurizing a building. It should be noted that leakage values of the top separation, given in Table 2, include leakage flows through the closed exhaust dampers at the top of the return and exhaust systems (shut down during the tests).

The dependence of the exterior wall air leakage rates on pressure difference is shown in Fig. 3. These air leakage rates varied from 0.12 to 0.18 cfm per sq ft of wall area at a pressure difference of 0.30 in. of water pressure and constituted from 20 to 55% of the over-all air leakage rates of the test buildings. These values are well above the standard [2] specified by the National Association of Architectural Metal Manufacturers (NAAMM): 0.06 cfm per sq ft of wall area at the same pressure difference. The exterior facades of three of the test buildings, D, E and H, were constructed of metal panels; those of the remaining test buildings were of precast concrete panels. As the wall materials are relatively impermeable to air, it is probable that the air leakage rates depended mainly on the design of wall joints and the way they were put together. Buildings E and H, which were constructed with close supervision of workmanship on wall jointing to minimize air infiltration, gave the lowest leakage rates; and where joint seals appeared inadequate, remedial measures were taken.

CALCULATION OF INFILTRATION RATE CAUSED BY STACK ACTION

Air infiltration in a building is caused by both wind and stack action. The calculation of infiltration rates caused by wind is quite complex, for the wind pressure distribution over the surface of a building depends on wind speed and direction, building shape and the nature of the surrounding terrain, including adjacent buildings. The literature on wind pressures on actual and model buildings in boundary-layer wind tunnels is extensive. Pressure measurements have been made primarily to develop data for structural load calculations and not for infiltration calculations, which require more detailed data on wind pressures both horizontally and vertically. If wind pressure data for a building are available, infiltration rates caused by both wind and stack action can be calculated with the aid of a digital computer and an appropriate mathematical model.[3,4,5]

The infiltration rates caused by stack action alone, which tends to govern the infiltration rate of a multi-storey building during cold weather, can be calculated relatively easily. The derivation of the equation is as follows:
Theoretical pressure difference across exterior walls caused by stack effect is given by[6]

$$\Delta P = 0.52\ p\ h \left(\frac{\Delta T}{T_i T_o}\right) \qquad (2)$$

where

p = barometric pressure, lb/sq in.

h = vertical distance from neutral zone, ft
positive sign above neutral zone
negative sign below neutral zone

ΔT = temperature difference, $T_i - T_o$, F

T_i absolute temperature inside, R

T_o = absolute temperature outside, R

The neutral zone is the level at which inside and outside pressures are equal. Eq 2 indicates that ΔP and ΔT have the same signs for all locations above the neutral zone and, conversely opposite signs below the neutral zone. Thus there will be infiltration through the walls of the lower storeys and exfiltration through the walls of the upper storeys when the temperature inside the building is higher than the air temperature outside. This means that air flows upward within the building during the winter months. The flow pattern is reversed during the summer months when the air temperature outside is higher than that inside.

Actual pressure difference depends on the resistances to flow of both the exterior and interior separations. It is less than the theoretical pressure difference indicated by Eq 2 because of the resistance to air movement associated with interior components such as partitions, floor constructions and walls of vertical shafts. The upward flow caused by stack action during cold weather takes place from floor to floor through openings in the floor construction and through vertical shafts. It can be expected that most upward flow will occur in the vertical shafts because their resistance (friction losses) will be considerably less than that associated with floors, which act as resistances in series. For this discussion, therefore, the floor construction is considered to be air tight.

With this assumption, the theoretical pressure difference given by Eq 2 is that between outside the building and inside a shaft at the same level. It is distributed across the exterior walls, interior partitions and the walls of vertical shafts. The manner of distribution depends upon the resistance of each of these separations in relation to that of the combined resistances at the same level. If the resistances of the exterior and interior separations are uniform from floor to floor, the ratio of actual (exterior walls) to theoretical pressure differences will be constant for the whole height of a building.

Eq 2 can be modified to take this into account

$$\Delta P = 0.52\ \gamma\ p\ h \left(\frac{\Delta T}{T_i T_o}\right) \qquad (3)$$

where

γ = ratio of actual to theoretical pressure difference.

If the exterior wall is much tighter than the interior separations, the value of γ will approach unity; if it is much looser, the value of γ will approach zero. The values for γ determined experimentally for a few multi-storey office buildings[7] ranged from 0.63 to 0.88.

The rate of airflow through an infinitesimal area of the exterior wall is given by

$$dQ_w = C_w dA_w \, (\Delta P)^{n_w} \qquad (4)$$

where

dQ_w = air leakage rate through an area dA_w of the exterior wall, cfm

C_w = flow coefficient, cfm/(sq ft)(in. of water)^{n_w}

n_w = flow exponent

Combining Eq 3 and 4 gives

$$dQ_w = C_w \left[0.52 \, \gamma \, p \, h \left(\frac{\Delta T}{T_i T_o}\right)\right]^{n_w} S dh \qquad (5)$$

where

S = perimeter of the building, ft.

For a building with a constant cross-sectional area and a uniform distribution of leakage openings with height, an equation for the total air infiltration rate can be obtained by integrating Eq 5 from the ground level to the neutral zone. The neutral zone level can be expressed as βH where β is the ratio of the height of the neutral zone and the building height H in ft.

Thus,

$$Q_w = C_w S \left[0.52 \, \gamma \, p \left(\frac{\Delta T}{T_i T_o}\right)\right]^{n_w} \frac{(\beta H)^{n_w + 1}}{n_w + 1} \qquad (6)$$

where

Q_w is the total rate of infiltration for the whole building.

As this equation assumes a wall with a uniform air leakage characteristic, a separate infiltration heat loss calculation using Eq 3 and 4 should be made for the exterior walls of the ground floor since their air leakage values tend to be higher than those of other floors.

INFILTRATION HEAT LOSSES CAUSED BY STACK ACTION

From Fig. 3, air leakage values for a tight, average and loose wall were assigned arbitrarily for heat loss calculation. A flow exponent, n_w, of 0.65 was assumed for these walls (it varied from 0.50 to 0.75 for the test buildings). The flow coefficients were assumed as follows:

Wall Tightness	Air Leakage Rate, cfm/sq ft at 0.3 in. water	Flow Coefficient, C_w cfm/(sq ft)(in. water)$^{0.65}$
NAVFH	0.06	0.13
tight	0.10	0.22
average	0.30	0.66
loose	0.60	1.30

These values will probably apply to exterior walls of curtain wall construction with fixed glazing but not to exterior walls of masonry construction. Measurements on one building[8] of the latter construction indicated that its leakage rates are considerably higher than those shown on Fig. 3.

The equation for infiltration rate, Eq 6, can be simplified for practical purposes by assuming the following: γ = 0.80, p = 14.7 psia, T_i = 530R, n_w = 0.65, β = 0.50. Substituting these values in Eq 6

$$Q_w = 0.00971 \, C_w S \left(\frac{\Delta T}{T_o}\right)^{0.65} (H)^{1.65} \qquad (7)$$

The sensible heat load due to infiltration is given by:[8]

$$Y = 1.08\ Q_w \Delta T \qquad (8)$$

where

Y = sensible heat loss, Btu/hr

Substituting Eq 7 in Eq 8 gives

$$Y = 0.0106\ C_w S \left(\frac{1}{T_o}\right)^{0.65} \left(|\Delta T| H\right)^{1.65} \qquad (9)$$

The latent heat loss when indoor humidity ratio is to be maintained at a constant level is given by [9]

$$Z = 4800\ Q_w (W_i - W_o) \qquad (10)$$

where

Z = heat required to increase moisture content of infiltration air from W_o to W_i, Btu/hr

W_i = humidity ratio of indoor air, pounds of water per pound of dry air

W_o = humidity ratio of outdoor air, pounds of water per pound of dry air

Substituting Eq 7 in Eq 10 gives

$$Z = 50.9\ C_w S \left(\frac{\Delta T}{T_o}\right)^{0.65} H^{1.65} (W_i - W_o) \qquad (11)$$

Infiltration rates were calculated for the four air leakage values and various building heights using Eq 7, expressed in air changes per hour and assuming a floor plan 150 ft sq. A temperature difference of 70 F was assumed between indoor and outdoor air. The results of these calculations (Fig. 4) indicated that air change rates increase with building height as well as with increasing wall leakage values.

These values may be compared with the outdoor air requirement for ventilation. ASHRAE STANDARD 62-73 [10] gives the minimum required ventilation air without tempering or filtering as 15 cfm per person for general office space (0.15 cfm per sq ft, based on 10 persons per 1000 sq ft of floor area). This represents 0.9 air change per hour. As this value is much higher than the values shown on Fig. 4, it appears that air infiltration by itself will not usually satisfy the ventilation requirement.

The sensible and latent infiltration heat losses were calculated using Eq 9 and 11, assuming an indoor-outdoor temperature difference of 70 F, a humidity ratio for indoors of 0.0047 lb of water per lb of dry air (70 F, 30% RH) and one for outdoors of 0.0006 lb of water per lb of dry air (0 F, 80% RH). The results of the calculation given in Btu per hour per square foot of wall area are shown in Fig. 5 for various building heights. For this example, the latent heat losses are 28% of the sensible heat losses.

In Fig. 6, the infiltration heat losses (sensible plus latent) are compared with the total heat losses through the exterior walls (infiltration plus transmission). The over-all U value was assumed to be 0.30, with values of 0.15 for the insulated walls and 0.55 for double-glazed windows, which constituted 40% of the total wall area. Transmission heat loss was 21.0 Btu/(hr)(sq ft) at a temperature difference of 70 F. For a building with an average wall leakage value, the percentage of total heat loss contributed by air infiltration varied from 22 to 46% for building heights of 200 to 1000 ft, respectively; these values are reduced to 9 to 22% for buildings with relatively air-tight walls. As infiltration heat losses increase with building height, the significance of air tightness for walls of tall buildings is apparent.

The ventilation requirement for general office space of 15 cfm of outdoor air per person demands an outdoor air supply of 0.56 cfm per sq ft of outside wall area, assuming a floor dimension of 150 by 150 ft and floor height of 10 ft. Using Eq 8 and 10, the heat loss (sensible plus latent) was 55.6 Btu/(hr)(sq ft) of wall area at a temperature difference of 70 F and humidity ratio, indoors, of 0.0017 lb of water per lb of dry air and, outdoors, of 0.0006 lb of water per lb of dry air. This heating load imposed by ventilation air has been compared with those of transmission and infiltration through a wall of average air tightness in Fig. 7. It may be seen that the ventilation heating load is the largest component of the total heating load (infiltration plus transmission plus ventilation). For a 200-ft high building it constitutes 67% of the total heating load, whereas infiltration heating load is only 7%. ASHRAE Standard 62-73 permits reduction in the ventilation air to 5 cfm per person (0.05 cfm per sq ft of floor area) if the air is tempered and filtered. This reduction in ventilation air results in heat losses due to ventilation and infiltration of 40 and 42% of the total heat loss, respectively. During unoccupied periods with no ventilation air, the infiltration heat loss is 22% of the total for walls of average air tightness and 9% for tight walls.

These calculations recognized stack action alone at a given inside-outside temperature difference. It is probable that infiltration rates of tall buildings depend primarily on stack action during cold weather and average wind velocity. The infiltration rates calculated in the previous examples would have been somewhat higher if wind action had also been considered. A complete analysis would involve integration of heat losses over the seasons, taking into account both wind and stack action.

HEAT LOSSES CAUSED BY BUILDING PRESSURIZATION

HVAC systems are sometimes designed and operated to minimize air infiltration, particularly at the entrance level, by means of building pressurization. Its effect is to increase the inside pressures and thereby lower the level of the neutral zone. If the neutral zone is lowered to ground level, air infiltration is eliminated but air exfiltration is increased. The required rate of supply of outside air to achieve this can be calculated from Eq 6 ; for this, the value of β, the ratio of the neutral zone height to building height, is taken as unity. The ratio of total exfiltration rate with pressurization (β = 1.0) to infiltration rate without pressurization (β = 0.5) is about 3.2; i.e., the outside supply air rate required to pressurize a building fully is 3.2 times the infiltration rate. This value would be greater if the exfiltration rate through the top of the building were also considered. Reducing infiltration rate by pressurization incurs a high heating cost penalty. It is more economical to pressurize the ground floor only, provided the ground floor enclosure is reasonably air tight.

CONCLUSIONS

1. The air leakage rates of the exterior walls of eight test buildings varied considerably, with values of 0.12 to 0.48 cfm per sq ft of wall area at a pressure difference of 0.30 in. of water. They were much above that specified by an industry standard of 0.06 cfm per sq ft of wall area at the same pressure difference.

2. For a wall with average air tightness and U value of 0.30 Btu/(hr)(sq ft)(F), the percentage of total heat loss through the walls contributed by infiltration during cold weather varied from 22 to 46% for building heights of 200 to 1000 ft, respectively; these values are reduced to 9 to 22 for buildings with relatively air-tight walls. They indicate the necessity of assuring relatively air-tight walls for tall buildings.

3. Air infiltration alone cannot be relied upon to provide an adequate amount of outdoor air for ventilation of buildings with curtain wall construction and fixed glazing. The heating load caused by ventilation air was found to be a major component of the total heating load.

4. Reducing air infiltration by mechanically pressurizing a building can mean a high heating cost penalty.

REFERENCES

1 C.Y. Shaw, D.M. Sander, G.T. Tamura, "Air Leakage Measurements of the Exterior Walls of Tall Buildings," ASHRAE TRANSACTIONS, vol 79, part 2, 1973, pp. 40-48.

National Association of Architectural Metal Manufacturers, Metal Curtain Wall Manual, Specifications, pp. 4-9, December 1962.

3 P.J. Jackman, "A Study of the Natural Ventilation of Tall Office Buildings," Journal of the Institute of Heating and Ventilating Engineers, vol 38, August 1970, pp. 103-118.

4 R.E. Barrett and D.W. Locklin, "Computer Analysis of Stack Effect in High-Rise Buildings," ASHRAE TRANSACTIONS, vol 74, part II, 1968, pp. 155-169.

D.M. Sander and G.T. Tamura, "Simulation of Air Movement in Multi Storey Buildings," presented at Second Symposium on the Use of Computers for Environmental Engineering Related to Buildings, Paris, 13-15 June 1971.

ASHRAE HANDBOOK OF FUNDAMENTALS, Chapter 19, "Infiltration and Natural Ventilation," 1972.

7 G.T. Tamura and A.G. Wilson, "Pressure Differences Caused by Chimney Effect in Three High Buildings," ASHRAE TRANSACTIONS, vol 73, part II, 1967, pp. II. 1.1 - II. 1.10.

8 G.T. Tamura and A.G. Wilson, "Pressure Differences for a Nine-Storey Building as a Result of Chimney Effect and Ventilation System Operation," ASHRAE TRANSACTIONS, vol 72, part I, 1966, pp. 180-189.

9 ASHRAE HANDBOOK OF FUNDAMENTALS, Chapter 21, "Heating Load," 1972.

10 ASHRAE STANDARD 62-73, "Standards for Natural and Mechanical Ventilation," 1973.

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TABLE 1

Description of Test Buildings

Building		B	C	D	E	F	G	H
Year constructed	1970	1964	1970	1971	1968	1973	1974	[illegible]
Year tested	1970	1971	1971	1971	1974	1974	1971	[illegible]
No. of typical floors	9	17	20	20	21	16	23	20
Floor plan (ft x ft)	156x210	88x140	126x146	75x93	83x158	83x183	123x145	126x146
Floor height (ft)	13	11	10.6	10.3	10.4	10.6	10.6	[illegible]
Wall area per floor (sq ft)	9,776	5,016	5,766	3,528	5,013	5,656	5,639	[illegible]
Window area (% wall area)	38	33	30	26	35	52	26	40
Window type	Fixed sealed double glazing	Openable sealed double glazing (key locked)	Fixed sealed double glazing	Fixed sealed double glazing	Fixed sealed double glazing	Fixed sealed double glazing	Fixed sealed double glazing	Fixed sealed double glazing
Wall construction	Precast concrete 4-in. tile 2-in. insulation air space 6-in. tile plaster	Precast concrete panel 2-in. insulation	Precast concrete panel air space 1-in. insulation 1/2-in. cement 6-in. concrete block plaster	Metal panel air space 2-in. insulation 20-in. concrete	Metal panel 2-in. insulation	Precast concrete panel 1-in. insulation	Precast concrete panel 1-in. insulation	Metal panel 2-in. air space 3.5-in. insulation

TABLE 2

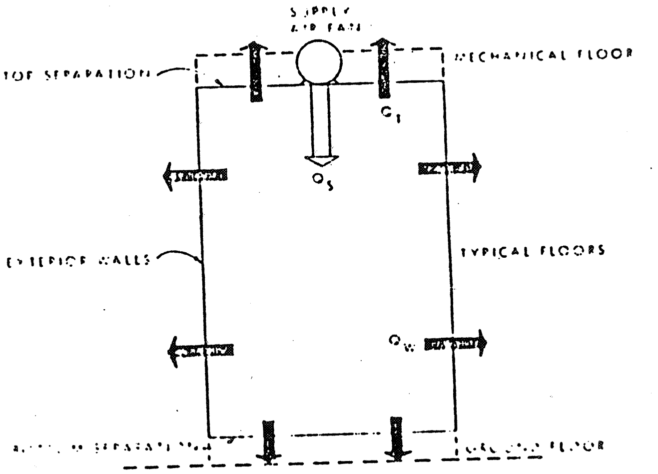
Flow Coefficients and Exponents of Test Buildings

Test Building	Outside Wall C_w	n_w	Bottom Separation C_b	n_b	Top Separation C_t	n_t
A	1.12	0.70	3.21	0.70	0.85	0.60
B	0.69	0.50	0.44	0.70	3.42	0.50
C	0.62	0.75	1.27	0.50	5.69	0.70
D	0.76	0.65	0.27	0.50	7.20	0.50
E	0.48	0.50	0.21	0.70	4.35	0.50
F	0.30	0.50	1.01	0.50	2.38	0.50
G	0.81	0.65	0.11	0.70	6.82	0.65
H	0.20	0.50	6.55	0.70	2.90	0.50

C_w in cfm/(sq ft of wall area)(in. of water)^{n_w}

C_b in cfm/(sq ft of floor area)(in. of water)^{n_b}

C_t in cfm/(sq ft of floor area)(in. of water)^{n_t}



$$Q_S = Q_W + Q_B + Q_T$$

Q_S = OUTSIDE SUPPLY AIR
Q_W = LEAKAGE FLOW THROUGH WALLS
Q_B = LEAKAGE FLOW THROUGH BOTTOM SEPARATION
Q_T = LEAKAGE FLOW THROUGH TOP SEPARATION

Fig. 1 Flow balance under wall leakage tests

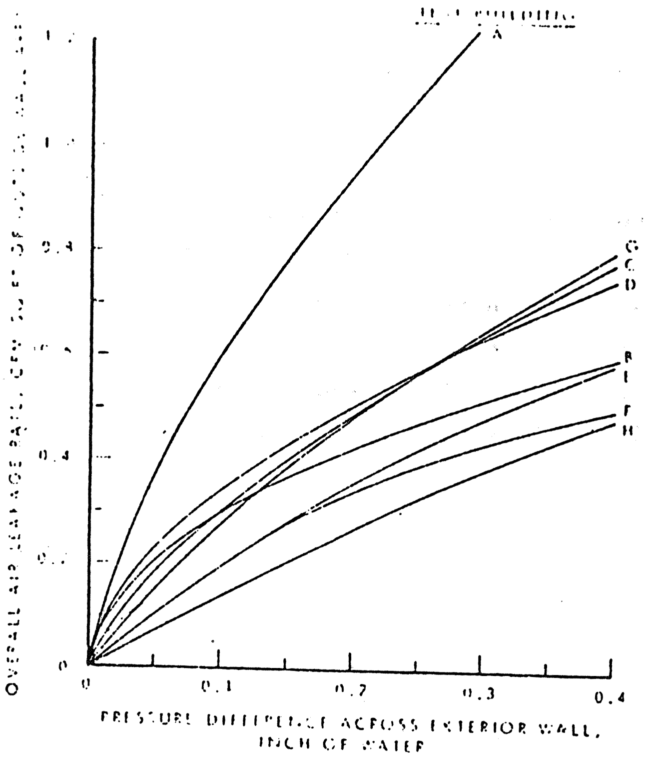
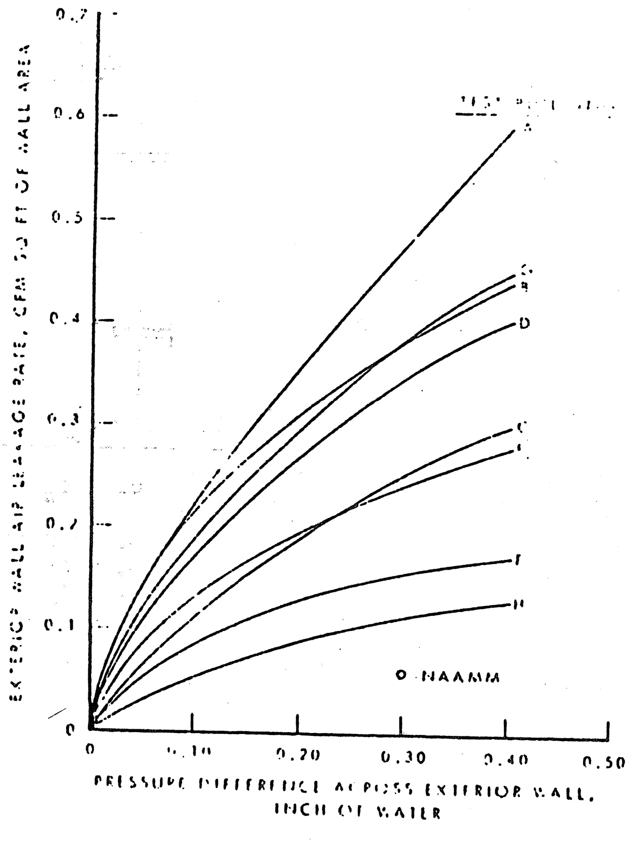


Fig. 2 Over-all air leakage rates of pressurized enclosure

Fig. 3 Air leakage rates of exterior walls



DISCUSSION

DAVID T. HARRJE, Senior Research Engineer and Lecturer, Princeton Univ., Princeton, NJ: Has there been any attempt to use the central shaft with blowing downward at the neutral line to attempt to benefit both the upper and lower portions of the building through reduced air infiltration?

TAMURA: Computer studies on this approach to reduce infiltration are given in a paper entitled "Building Pressures Caused by Chimney Action and Mechanical Ventilation" by A.G. Wilson and myself (ASHRAE TRANSACTIONS, vol. 73, Part II, 1967). The reduction of pressure differences across the exterior walls would depend on the recirculation rate and the internal resistence of a building; inside pressures of a building with a low internal resistance will not be altered significantly to affect the pressure differences across the exterior walls.

It should be recognized that if both infiltration and exfiltration are eliminated by this means, then the pressure differences caused by stack action would be transferred from the exterior walls to the walls of vertical shafts which can give rise to difficulties in operating elevator and stair doors. It is probable that effective operation of this system with changing condition of wind and stack action would be difficult. The preferred approach to minimize infiltration is contructing outside walls that are relatively air tight rather than by using ventilation fans as suggested or for building pressurization.

RONALD N. JENNER, NASA, Hampton, VA: In regards to infiltration due to wind on low-rise building, what does your study show?

TAMURA: It was stated that infiltration rates of high rise buildings depend primarily on stack action during cold weather and average wind velocity. It is expected that the effect of wind action compared to that of stack action would be greater for low-rise buildings than for high-rise buildings; that due to stack action, however, it should not be neglected as field studies indicate that even for houses its effect is significant.

INFIL

An Algorithm for Calculating Air Infiltration

It is well recognized that the air infiltration constitutes as much as 30% of home heating load and a significant part of the load of non-pressurized commercial buildings. The air leakage of a building depends upon the tightness of its exterior walls, windows, and doors; the wind characteristics and temperature difference between the inside and outside, and to some extent how the building is operated with respect to the opening and closing of its door.

The rate of air infiltration can be empirically expressed by

Q = C*A*ΔP**N

where

- Q: air flow rate
- C: flow coefficient
- A: flow opening area
- N: pressure exponent
- ΔP: pressure difference

Unfortunately it is very difficult to determine accurate values of flow opening area and pressure difference for actual buildings, which consist of complex air leakage passages. A limited amount of data are given in the 1972 ASHRAE Handbook of Fundamentals for equivalent opening area of typical windows, doors and walls. The pressure difference depends upon wind characteristics around the building and the temperature difference between the inside and the outside of the building.

Compiled in this section is a methodology to approximately calculate the pressure difference between a given space and its adjacent space including the outdoor. The basic mathematical principle involved is to attain a solution to a set of pressure difference equations of the following type:

$$Q_i = \Sigma Q_{i,k} = 0$$

$$Q_{i,k} = \Sigma A_{i,k} * C_{i,k} * (P_i - P_k) ** N_{i,k}$$

where

Q_i: net air flow out of space i

$Q_{i,k}$: air exchange between space i and space k

$A_{i,k}$: flow opening area between space i and k

$C_{i,k}$: flow coefficient applicable to the air flow between the spaces i and k

$N_{i,k}$: pressure exponent applicable to the flow between the spaces i and k

A special computational routine is required to solve this set of simultaneous, non-linear equations.

As mentioned previously, air leakage through various openings such as doors, windows, window frames, pinholes in the wall and service shafts may be approximated by an equation of the following type:

LEAK = 4000 * A * K * (DP) ** N

= C * (DP) ** N

where

LEAK = air leakage in cu. ft per min.

A = opening area, sq ft

K = flow coefficient, dimensionless

DP = pressure difference across the opening, inches of water

N = pressure exponent, dimensionless

C = equivalent flow coefficient (EFC)

The values of K and N vary depending upon the type of opening. Moreover, the exact value of A is not well known for many types of openings, such wall pinholes or cracks around the windows. Table A-17 lists the values of Equivalent Flow Coefficient C and the flow exponent N for various types of openings common to many buildings. These values are derived from the air leakage data compiled in Chapter 19 "Infiltration and Natural Ventilation" of the 1972 ASHRAE Handbook of Fundamentals.

Table A-17

	C	N
1. Double-hung wooden windows (locked)*		
non-weatherstripped loose fit	6	0.66
average fit	2	0.66
weatherstripped loose fit	2	0.66
average fit	1	0.66
2. Window frames*		
masonry frame with no caulking	1.2	0.66
masonry frame with caulking	0.2	0.66
wooden frame	1	0.66
3. Swinging doors* 1/2" crack	160	0.5
1/4" crack	80	0.5
1/8" crack	40	0.5
4. Walls** 8" plain brick	1	0.8
8" brick and plaster	0.01	0.8
13" brick	0.8	0.8
13" brick and plaster	0.004	0.7
13" brick, furring, lath and plaster	0.03	0.9
frame wall, lath and plaster	0.01	0.55
24" shingles on 1 x 6 boards on 14" center	9	0.66
16" shingles on 1 x 4 boards on 5" center	5	0.66
24" shingles on shiplap	3.6	0.7
16" shingles on shiplap	1.2	0.66

* Values of C listed for these openings are per ft of linear crack length.

** Values of C listed for the walls are per unit area of the wall surface.

In many instances, detailed information of air leakage characteristics is not available, but it is still possible to make a calculation. For a modern office building of 120 ft x 120 ft plan dimension with the floor height of 12 ft, Tamura[15/] lumped together all the leakage area for a given floor as follows:

Table A-18

outside wall	2.5 sq. ft per story
4 elevator shaft doors	4.5 " " " "
2 stair shaft doors	0.5 " " " "
floor	3.7 " " " "
brench perimeter and interior air duct	7.0 " " " "
return duct	14.0 " " " "
vertical shafts (elevator or stairwell)	1/3 of the cross-sectional area*

The value of C corresponding to these data can be obtained by multiplying them by 2400 which corresponds to K = 0.6.

<u>Data</u>:

V: Wind speed measured at a 40 ft elevation as taken from the weather tape, knots

DIR: Wind direction measured clockwise from North, degrees (see Figure A-21)

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* This particular data were derived from a recent and unpublished experiment of the National Bureau of Standards conducted on two high-rise ildings.

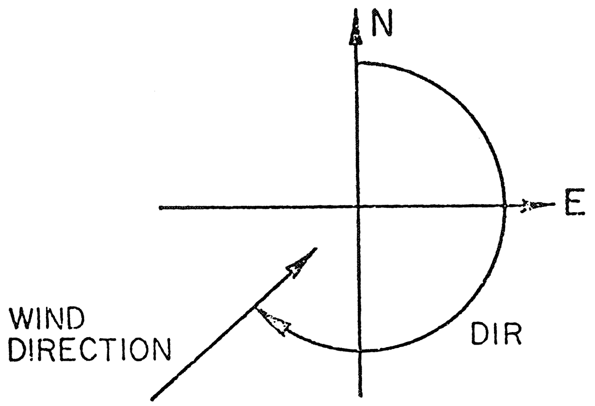


Figure A-21 Definition of Wind Direction Angle

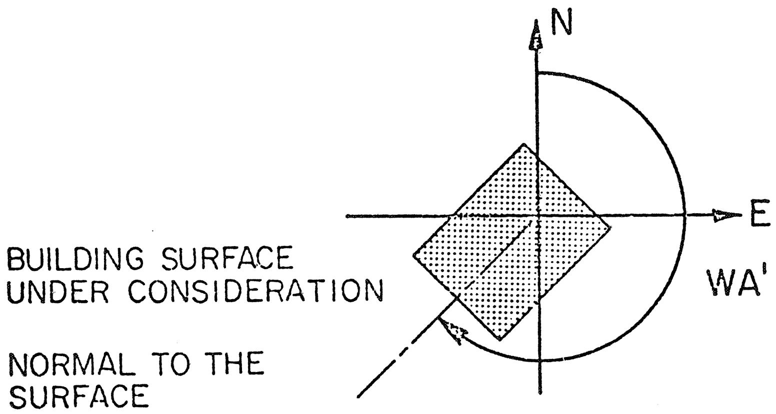


Figure A-22 Definition of the Angle Between North and Normal of the surface Under Consideration

DB: Outdoor air dry-bulb temperature, F

PB: Barometric pressure, in. Hg.

NF: Number of above-grade floors

HTT: Total height of building (from above-grade), ft

TZ: Indoor air temperature, F

TS: Elevator and service shaft temperature

WA': Direction angle of the building as defined with respect to North and the normal of the principal surface of the building (see Figure A-22)

HT_k: Height of the floor, ft, for k = 1, 2, 3, ... NF

$CFMSP_k$: Ventilation air supplied to the floor, cu ft per min, for k = 1, 2, 3, ... NF

$CFMEX_k$: Ventilation air exhausted from the floor, cu ft per min, for k = 1, 2, 3, ... NF

Calculation Sequence:

1. V' = 1.153 * V

   TO = 460 + DB

   TI = 460 + TZ

   PO = 0.4910 * PB

   x = DIR - WA'

2. Wind velocity, VH, at height HT on the building, mph

   VH = V' * 0.117 * (1 + 2.81 * Log (0.305 * HT + 4.75))

3. Theoretical wind velocity pressure, PTWV on the building, in. H_2O

   PTWV = 0.000482 * (V ** 2)

4. Wind direction, BWD, relative to building surfaces

BWD = 1 surface on windward side if,

$-45° < x < +45°$

BWD = 2 surface on leeward side if,

$90° < x < 270°$

or, $-90° < x < -270°$

BWD = 3 surface on side if,

$45° < x < 90°$

or, $-45° < x < 90°$

5. Using Table A-19, determine the normal wind velocity pressure correction factor, PTKN

Table A-19 Values of PTKN

	TB = 1			TB = 2			TB = 3		
NSB	BWD = 1	BWD = 2	BWD = 3	BWD = 1	BWD = 2	BWD = 3	BWD = 1	BWD = 2	BWD = 3
0.5	.1	-.3	-.8	-.5	-.25	-.45	.5	.45	.45
1.0	.1	-.25	-.5	-.5	-.2	-.3	.45	.3	.3
2.0	.1	-.25	-.4	.0	-.2	-.3	.45	.1	.1
3.0	.1	-.25	-.4	.1	-.2	-.35	.45	.0	.0
5.0	.25	-.35	-.6	.25	-.25	-.45	.5	-.1	-.1
∞	.6	-.35	-.7	.6	-.35	-.7	.6	-.35	-.7

where

TB = 1: Shorter building on windward side

TB = 2: Equals taller building on windward side

TB = 3: Taller building on leeward side

NSB: Ratio of the distance between the adjacent buildings and the width of the building in the direction of wind

6. Wind velocity pressure correction factor, PTKO, for winds obliquely to the wall surface

If BWD = 1 (windward side of building)

$(PTKO)_m = \text{Cos}\ (|\ x\ |)$

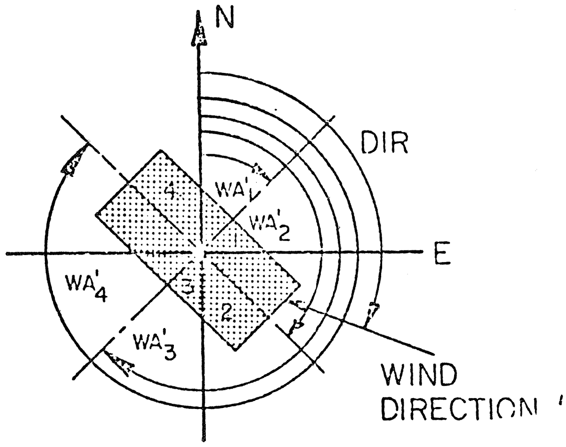
If BWD = 2 (leeward side of building)

$(PTKO)_l = 1.0$

If BWD = 3 (side of building)

$(PTKO)_s = \text{Cos}\ (|\ x\ |)$

Example:



DIR = 110°

$WA_1' = 45°$

$WA_2' = 135°$

$WA_3' = 225°$

$WA_4' = 315°$

Figure A-23 DIR and WA' Angles of Example

Side 1, $DIR\text{-}WA_1' = 110° - 45° = 65°$ (therefore, BWD = 3)

Side 2, $DIR\text{-}WA_2' = 110° - 135° = -25°$ (therefore, BWD = 1)

Side 3, $DIR\text{-}WA_3' = 110° - 225° = 115°$ (therefore, BWD = 2)

Side 4, $DIR\text{-}WA_4' = 110° - 205° = 205°$ (therefore, BWD = 2)

Side 1, $(PTKO)_s = \text{Cos}\ (+65°)$

Side 2, $(PTKO)_m = \text{Cos}\ (+25°)$

Side 3, $(PTKO)_1 = 1.0$

Side 4, $(PTKO)_1 = 1.0$

7. Actual wind pressure on the building at height (HT) corresponding to floor (k): $(PAWV)_k$

   $(PAWV)_k = (PTKO)_k * (PTKN)_k * (PTWV),$

8. Stack effect pressure (PSE) on the outside of the building at building height (HT) and floor (k), in. H_2O

   $(PSE)_k = -0.52 * PO * HT/TO$

9. Total pressure on the outside of the building (PCO) at floor (k), in. H_2O

   $(PCO)_k = (PAWV)_k + (PSE)_k$

10. Pressure in the elevator and serve shafts (PSE) at height (HT) corresponding to floor (k), in. H_2O

   $(PSE)_k = -0.52 * PO * HT/TI + (PSE)_1$

11. Choose appropriate flow coefficients and pressure exponents for air leakage paths of each floor as follows:

   Flow coefficients

   CWD: Value of C for appropriate window in Table A-17 multiplied by the total crack length of all the windows

CFM: Value of C for appropriate window frame in Table A-17 multiplied by the total crack length of all the window frames

CDR: Value of C for appropriate door in Table A-17 multiplied by the total crack length of all the doors

CWL: Value of C for appropriate walls in Table A-17 multiplied by the total wall area

CCL: Value of A for the ceiling from Table A-18 multiplied by 2400

CFL: Value of A for the floor from Table A-18 multiplied by 2400

CEL: Value of C for elevator doors

CSS: Value of C for the doors to the service shaft

CFS and CES: Value of the cross section of the shaft multiplied by 800

Pressure exponent

NWD: Value of N for the appropriate window in Table A-17

NFM: Value of N for the appropriate window frame in Table A-17

NDR: Value of N for the appropriate door in Table A-17

NWL: Value of N for the appropriate wall in Table A-17

NCL: 0.5

NFL: 0.5

NEL: 0.5

NSS: 0.5

NFS: 0.5

NSE: 0.5

12. Solution of 2 * NF equations

Outdoor air leakage to k-th floor rooms* (see Figure A-23)

Window k leakage

$$LEAKWD_{k,j} = CWD_{k,j} * (PCO_{k,j} - PI_k) ** NWD_{k,j} \quad (1)$$

Window frame leakage

$$LEAKFM_{k,j} = CFM_{k,j} * (PCO_{k,j} - PI_k) ** NFM_{k,j} \quad (2)$$

Door leakage

$$LEAKDR_{k,j} = CDR_{k,j} * (PCO_{k,j} - PI_k) ** NDR_{k,j} \quad (3)$$

Wall leakage

$$LEAKWL_{k,j} = CWL_{k,j} * (PCO_{k,j} - PI_k) ** NWL_{k,j} \quad (4)$$

Ceiling leakage

$$LEAKCL_k = CCL_k * (PI_{k+1} - PI_k) ** NCL_k \quad (5)$$

Floor leakage

$$LEAKFL_k = CFL_k * (PI_{k-1} - PI_k) ** NFL_k \quad (6)$$

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* In all of above expressions, subscript k refers to the k-th floor and subscript j refers to the j-th side of the building where the convention is j = 1 (south), 2 (west), 3 (north), and 4 (east).

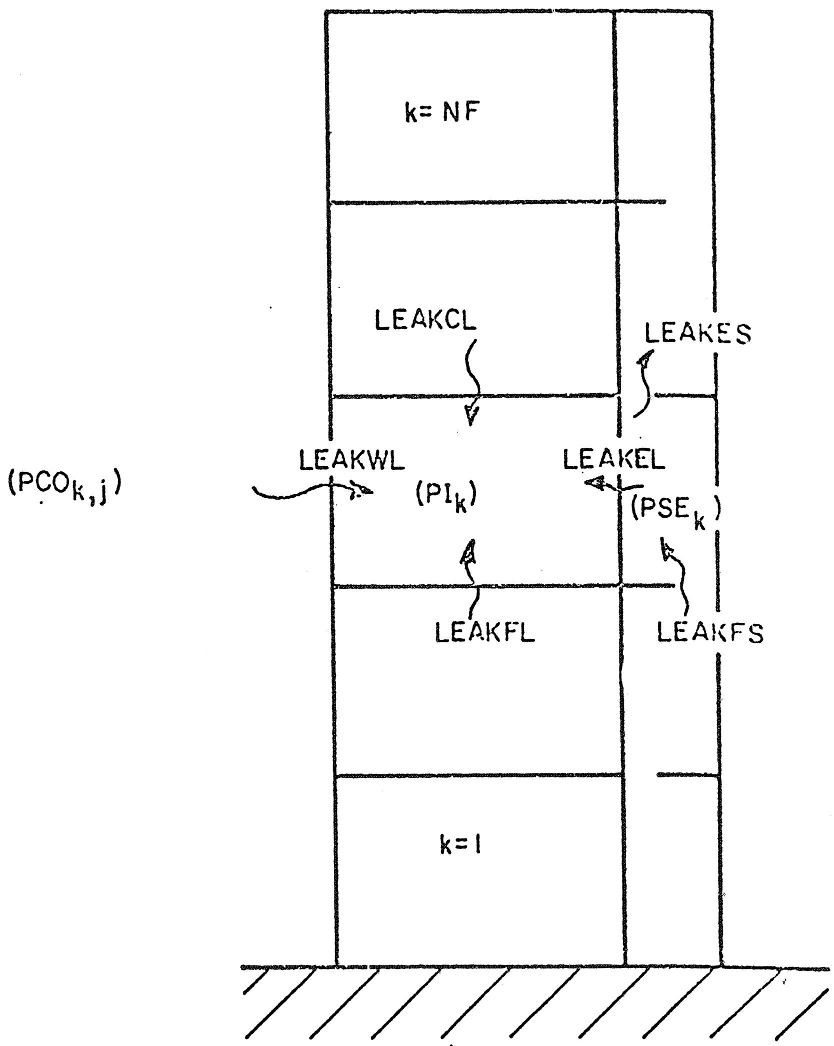

Figure A-23 Air Leakage Pattern of a High-Rise Building

Leakage from the elevator and service shafts*

$$LEAKEL_k = CEL_k * (PSE_k - PI_k) ** NEL_k \quad (7)$$

$$LEAKSS_k = CSS_k * (PSE_k - PI_k) ** NSS_k \quad (8)$$

Air leakage between the floor levels within the shafts*/

$$LEAKFS_k = CFS_k * (PSE_{k-1} - PSE_k) ** NFS_k \quad (9)$$

$$LEAKES_k = CES_k * (PSE_{k-1} - PSE_k) ** NSE_k \quad (10)$$

In the previous equations, unknowns are PI_k for k = 1, 2, 3, ... NF and PSE_k for k-1, 2, 3 ... NF provided that the pressures in all the shafts are assumed equal at a given floor level.

Flow balance equations at the k-th floor (the individual quantities come from equations 1-10 above)

Rooms

$$LEAKWD_{k,j} + LEAKFM_{k,j} + LEAKDR_{k,j} + LEAKWL_{k,j} + LEAKCL_k + LEAKFL_k + LEAKEL_k + LEAKSS_k + CFMSP_k - CFMEX_k = 0$$

---

* In all of above expressions, subscript k refers to the k-th floor and subscript j refers to the j-th side of the building where the convention is j = 1 (south), 2 (west), 3 (north), and 4 (east).

Elevator Shaft or Service Shaft

$$LEAKFS_k + LEAKES_k - LEAKEL_k{}^* + CFMSPS_k - CFMEXS_k = 0$$

where $CFMSPS_k$: ventilation air supplied at the k-th floor in the shaft

$CFMEXS_k$: air exhausted from the shaft at the k-th floor

These 2 * NF sets of flow balance equations must be solved by an appropriate iteration technique to obtain the pressure profiles in the building and in the shafts. Then the calculated pressure values are used to determine the air leakage of the building.

Recently a comprehensive computer program that embodies the basic algorithm described in this section was published by D. M. Sander and G. T. Tamura of the National Research Council of Canada. The details of the program are given in an NRC booklet entitled "A Fortran IV Program to Simulate Air Movement in Multi-Storey Buildings", DBR Computer Program No. 35, (March 1973).

* If this equation were for a service shaft, $LEAKEL_k$ would be replaced by $LEAKES_k$.

APPENDIX C

RESIDENTIAL BUILDING MODELS

9.5 Air Infiltration Analysis

The analysis of the infiltration was divided into two categories. The first category consists of linear models which are similar in format to those presented by previous investigators. Due to the enormous quantity of data collected, it was felt that the linear models could be analyzed statistically and ultimately be generalized into a unified model applicable for any residence. The subsequent failure of this approach then led to the development of the second category.

The second method of analysis was based on the development of a model formed from the physical variables and theory associated with air infiltration. The variables considered were crack lengths, crack widths, pressure differences due to wind and temperature effects, location of neutral zone and the interaction of pressure differences due to wind and temperature effects. Again, statistical analysis was employed to develop a generalized model which has the capability to be applicable for any residence.

9.5.1 Linear Models

The initial development of an air infiltration model was based on the following model:

$$INF = A + B(\Delta T)^n + C(Vel)^n \qquad (9.5.1)$$

INF = Air Infiltration, air changes or cfm

ΔT = Indoor-Outdoor Temperature Difference, °F

Vel = Wind Speed, mph

A,B,C = Statistical Regression Coefficients

n = Exponent, 1/2 or 1

which is similar to that proposed in (9.3.18). The initial problem associated with this model was in the determination and interpretation of the leading coefficient A. Implied in this term is the concept that infiltration occurs when the independent variables are zero. This leading coefficient had also been observed in the study conducted at the National Bureau of Standards in the environmental control test chamber under very controlled conditions. Specifically, the wind effects were entirely deleted. It had been postulated that minor, less than 1 mph, wind effects actually occur and were not measured which accounted for this effect, but the NBS research dispelled that theory. A second theory was proposed which stated that minor thermal gradients exist even when the integrated hourly average temperature differences were zero. Verification of this thermal effect has never been proven. Rather a third concept of measurement error was proposed but then later rejected, again by NBS, by using various measurement techniques to substantiate the magnitude of A. Convinced that A did exist, a statistical analysis was conducted to determine its magnitude.

The air infiltration data collected at the CTSE site was used to establish the value of A because of the absence of the effects of occupancy. Procedurally, the measured data was segregated into four data sets by ranges of wind speed. The first data set contained wind speeds less than 1 mph, the second less than 2 mph, until a maximum of 4 mph was reached. Although wind speeds above 4 mph are still considered calm air it was felt that wind gusts could occur throughout an hour to cause instantaneous speeds greater than 4 mph and possibly influence the true value of A. A second argument arose in disfavor of using wind speeds greater than 4 mph when the statistical results were completed as presented in Table 9.5.1. Note that the correlation coefficient, R^2, rapidly decreased between data sets 3 to 4. Thus, the results of data set 3 were used and considered the most representative.

The information contained in data set 3 is plotted in Figure 9.5.1. The intercept, A, is projected to be 0.1187 but the measured data does not occur below a temperature difference of 4°F to verify the intercept. It is conceivable that the data could rapidly fall off to zero instead of extending to an intercept.

A comparison was then made among the model developed and that of previous researchers. The results are presented in Figure 9.5.2. The different slopes indicate a different temperature dependency but all three have recorded approximately

TABLE 9.5.1: TEMPERATURE EFFECT ON INFILTRATION AT SITE CTSE

	Mean	σ	T[1]	Prob > |T|[2]	DF[3]	R-SQUARE[4]
Data Set #1 Velocity less than 1 mph - 34 hours of data						
INF = 0.1206 + 0.00885 (TDIFF)						
INTERCEPT	--	--	4.18	0.0001	--	--
TDIFF	19.36	6.17	6.15	0.0001	34	--
INF	0.292	0.036	--	--	1	0.792
Data Set #2 Velocity less than 2 mph - 64 hours of data						
INF = 0.0972 + 0.0105 (TDIFF)						
INTERCEPT	--	--	5.60	0.0001	--	--
TDIFF	19.07	8.6	12.68	0.0001	64	--
INF	0.298	0.057	--	--	1	0.722
Data Set #3 Velocity less than 3 mph - 94 hours of data						
INF = 0.1187 + 0.00981 (TDIFF)						
INTERCEPT	--	--	8.22	0.0001	--	--
TDIFF	19.53	11.23	15.30	0.0001	94	--
INF	0.429	0.070	--	--	1	0.715
Data Set #4 Velocity less than 4 mph - 122 hours of data						
INF = 0.1441 + 0.00945 (TDIFF)						
INTERCEPT	--	--	9.31	0.0001	--	--
TDIFF	20.72	13.2	15.30	0.0001	122	11
INF	0.455	0.089	--	--	1	0.661

(1) Student t-value for hypothesis that B = 0.0.

(2) Student t-test.

(3) Degrees of freedom.

(4) Correlation coefficient.

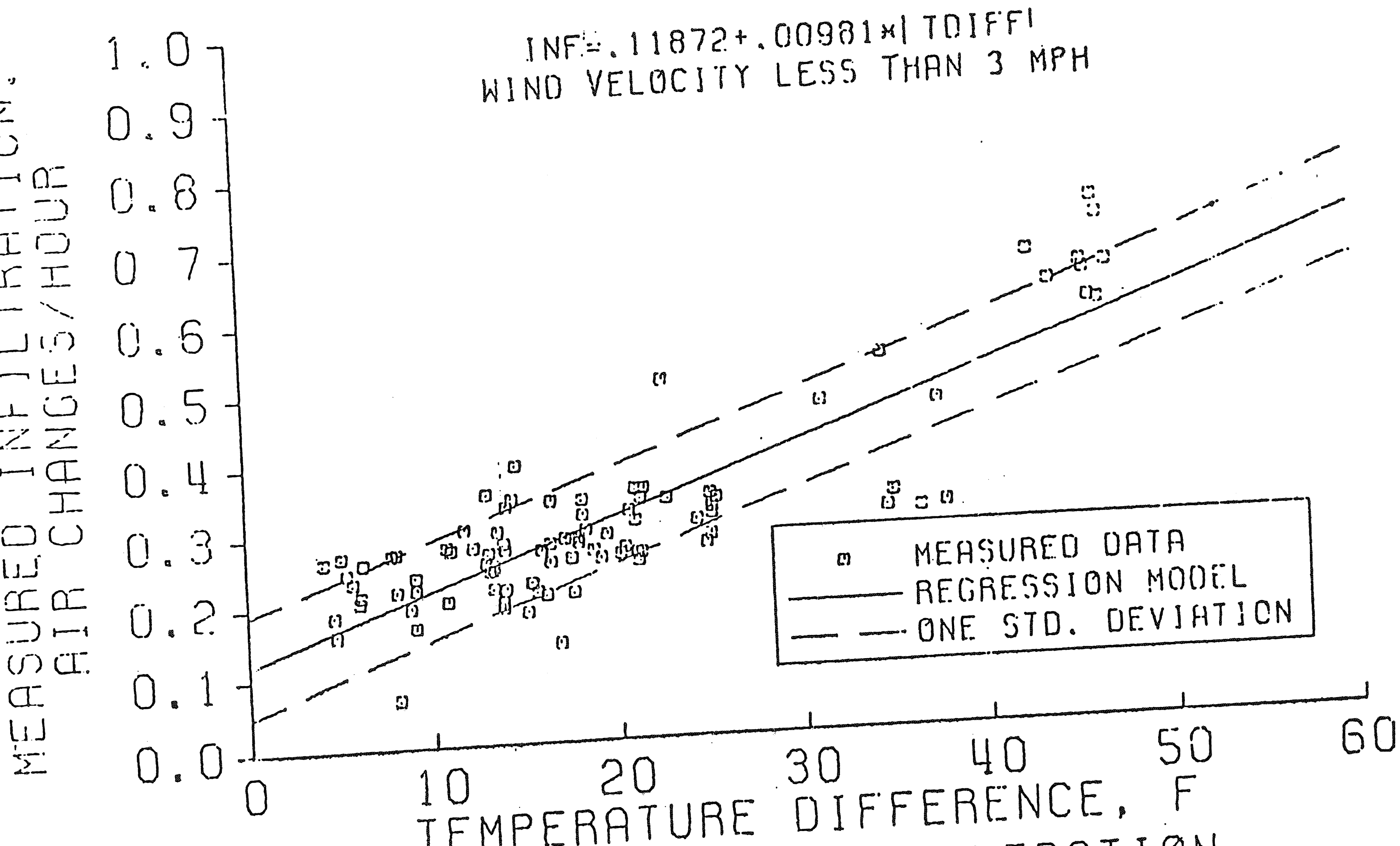

FIG.9.5.1 CONTROL HOUSE INFILTRATION TEMPERATURE EFFECT

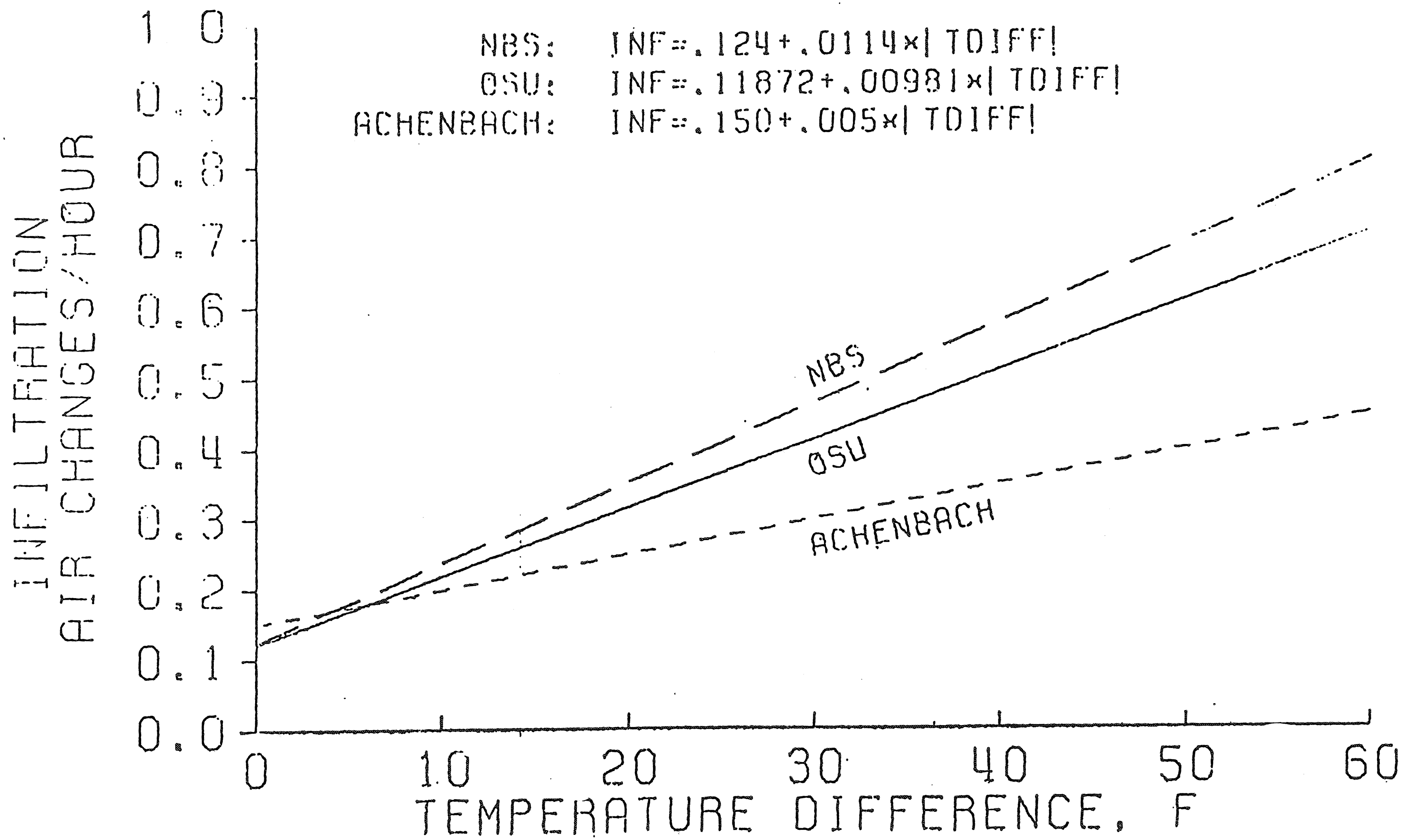

FIG. 9.5.2 COMPARISON OF TEMPERATURE EFFECTS

the same magnitude for the intercept A. Based on this analysis, a constant value of A was then used in the remaining analysis for the site where the data was collected and also, for the remaining eight sites in Columbus, Ohio where measured data was collected.

The next problem with the linear model was that the wind effects should account for wind direction. Previously, a broad-narrow side effect was postulated (9.3.24, 9.3.27, 9.3.28) as well as a normal component approach (9.3.23). The normal component was thought to be a more universal approach and formed the basis for the following wind term:

$$SF = 0.75 + 0.25\,(2(WD-HOS)) \qquad (9.5.2)$$

Where:

SF = Shape Factor

WD = Wind Direction, degrees

HOS = House Orientation, degrees

Next measured data was used to determine the magnitude of the shape factor by using:

$$SF = K(SF) \qquad (9.5.3)$$

Where:

K = Constant

The final value of K was 0.0668 as shown in Figure 9.5.3.

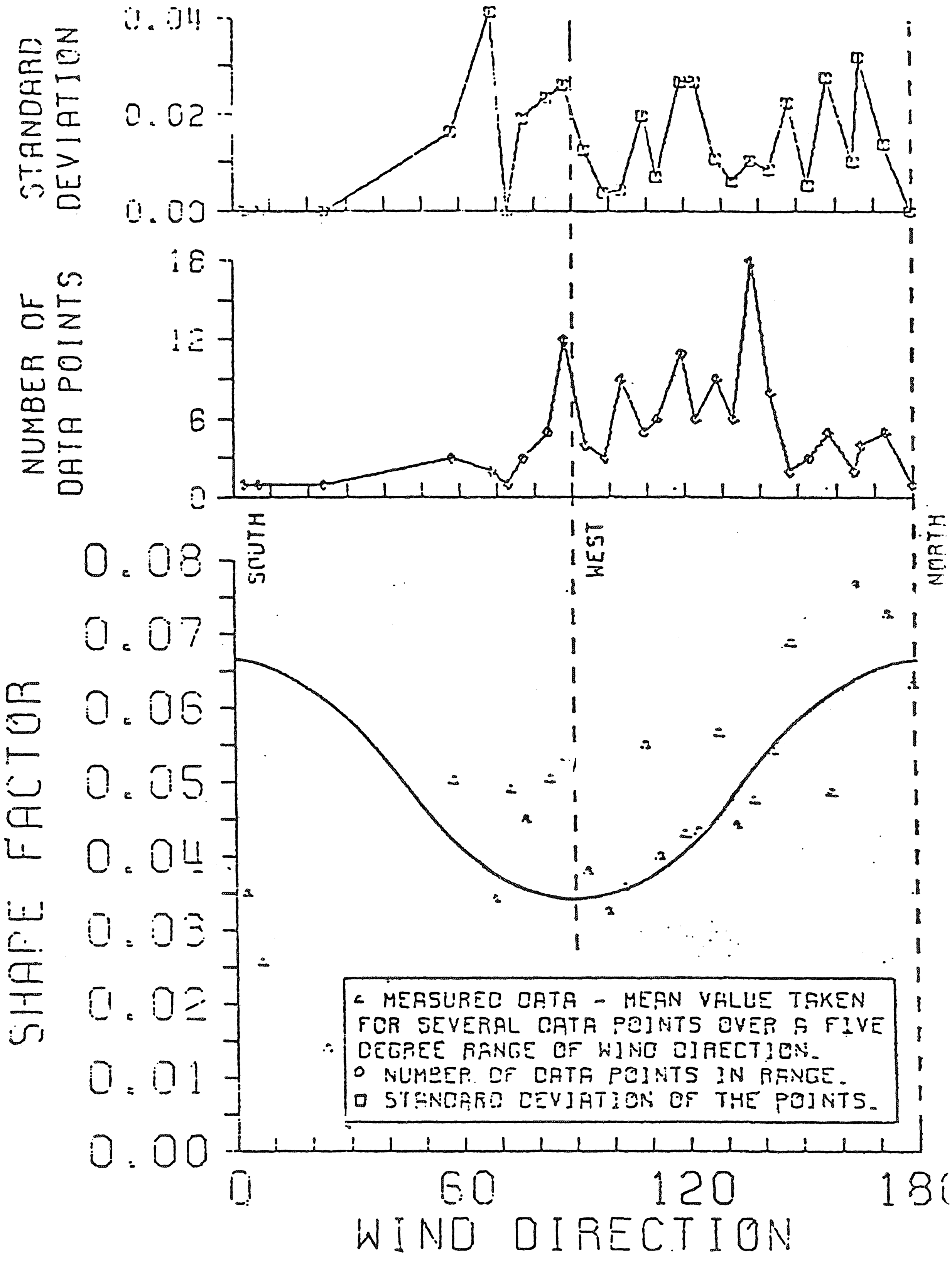

FIG.9.5.3 VELOCITY SHAPE FACTOR

Determination of the intercept, A, and the wind direction term completed the theoretical consideration in the linear model term. The final problem was to determine the exponent n. The physical conditions presented by combining Equations 9.3.14 and 9.3.16 suggest that n = 1 for the velocity term exponent. However, since the form of the equation was based strictly on a linear approach of the weather variables, a combination of terms was considered so that the best statistical model would result. A summary of the linear models is presented in Table 9.5.2. The results are shown in Tables 9.5.3 - 9.5.15.

9.5.2 Analysis of Linear Models

The results require some interpretation because of the subtle differences employed in the statistical procedures. The only difference occurs in the procedure used to determine the intercept A. In models L1-L6, the intercept was not specified but statistically determined to provide the best available fit to the measured data. Consequently, the statistical results were based on a sum of squared corrected for the mean which typically results in a lower correlation coefficient, R^2, and a lower coefficient of variance, C.V., than those results obtained when the intercept is not determined. Consequently, the rms error is a better term to use for comparison between the different models. Typically the rms errors range from 0.12 - 0.16 air changes with extremes of 0.08 - 0.40 air changes. The net conclusion obtained from reviewing the various models and their rms errors was that

TABLE 9.5.2

LINEAR MODELS

Model Identification	Model
L1	$INF = A + B(\Delta T) + C(Vel)$
L2	$INF = A + B(\Delta T) + C(SF \cdot Vel)^2$
L3	$INF = A + B(\Delta T) + C(Vel)^2$
L4	$INF = A + B(\Delta T)^{1/2} + C(Vel)$
L5	$INF = A + B(\Delta T)^{1/2} + C(SF \cdot Vel)^2$
L6	$INF = A + B(\Delta T)^{1/2} + C(Vel)^2$
L1A	$INF = 0.1187 + B(\Delta T) + C(Vel)$
L2A	$INF = 0.1187 + B(\Delta T) + C(SF \cdot Vel)^2$
L3A	$INF = 0.1187 + B(\Delta T) + C(Vel)^2$
L4A	$INF = 0.1187 + B(\Delta T)^{1/2} + C(Vel)$
L5A	$INF = 0.1187 + B(\Delta T)^{1/2} + C(SF \cdot Vel)^2$
L6A	$INF = 0.1187 + B(\Delta T)^{1/2} + C(Vel)^2$

The model identification is coded as:

a) First letter (L) indicates a linear model.

b) Second number indicates model number or form.

c) Third letter (A) indicates a constant (0.1187) was used for the intercept as determined from site CTSE.

TABLE 9.5.3

LINEAR MODEL RESULTS

SITE: CTSE

504 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.1219	0.0081	0.0231	0.846	21.9	0.0876
L2	0.1606	0.0085	0.0031	0.821	23.6	0.0947
L3	0.1633	0.0085	0.0014	0.837	22.6	0.0904
L4	0.0084	0.0645	0.0255	0.833	22.8	0.0913
L5	0.0488	0.0674	0.0035	0.797	25.1	0.1007
L6	0.0497	0.0679	0.0015	0.818	23.8	0.0954
L1A	0.1187	0.0082	0.0232	0.941	31.0	0.0877
L2A	0.1187	0.0099	0.0031	0.926	34.7	0.0980
L3A	0.1187	0.0100	0.0014	0.932	33.3	0.0942
L4A	0.1187	0.0413	0.0262	0.921	35.8	0.1012
L5A	0.1187	0.0518	0.0037	0.917	36.9	0.1042
L6A	0.1187	0.0527	0.0016	0.925	35.0	0.0991

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	4.89	178	56.3	75.5	0.4020
STD.DEV.	4.62	80	19.2	3.1	0.2239
LOW	0.00	3	21.1	66.8	0.1206
HIGH	20.20	360	92.4	80.3	1.1270

TABLE 9.5.4

LINEAR MODEL RESULTS

SITE: KTSC

389 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.1907	0.0023	0.0369	0.538	25.9	0.1295
L2	0.3884	0.0000	0.0044	0.438	28.5	0.1428
L3	0.3277	0.0016	0.0021	0.571	24.9	0.1248
L4	0.1294	0.0239	0.0370	0.539	25.8	0.1294
L5	0.3821	0.0001	0.0044	0.439	28.5	0.1428
L6	0.2875	0.0166	0.0021	0.571	24.9	0.1248
L1A	0.1187	0.0037	0.0401	0.907	34.1	0.1305
L2A	0.1187	0.0065	0.0059	0.861	41.8	0.1560
L3A	0.1187	0.0068	0.0026	0.899	35.6	0.1362
L4A	0.1187	0.0254	0.0373	0.909	33.8	0.1294
L5A	0.1187	0.0432	0.0053	0.879	38.9	0.1492
L6A	0.1187	0.0437	0.0023	0.911	33.3	0.1277

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	6.48	163	41.8	73.9	0.5028
STD.DEV.	4.08	89	11.7	1.9	0.1908
LOW	0.uu	18	15.3	70.0	0.1949
HIGH	19.90	330	89.0	80.6	1.3494

TABLE 9.5.5

LINEAR MODEL RESULTS

SITE: KTSC

37 OBSERVATIONS IN DATA SET: GAS

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.0926	-0.0029	0.0723	0.741	24.7	0.1650
L2	0.8371	-0.0111	0.0069	0.502	34.3	0.2288
L3	0.5766	-0.0058	0.0031	0.744	24.6	0.1639
L4	0.1231	-0.0268	0.0744	0.737	24.9	0.1662
L5	1.1372	-0.1210	0.0072	0.465	35.6	0.2371
L6	0.7198	-0.0615	0.0032	0.735	25.0	0.1668
L1A	0.1187	-0.0033	0.0709	0.938	29.4	0.1650
L2A	0.1187	-0.0005	0.0143	0.826	49.1	0.2757
L3A	0.1187	0.0023	0.0042	0.915	34.4	0.1930
L4A	0.1187	-0.0001	0.0003	0.937	29.6	0.1662
L5A	0.1187	0.0082	0.0129	0.828	49.0	0.2748
L6A	0.1187	0.0216	0.0040	0.921	33.1	0.1860

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	9.85	78	38.0	75.2	0.6957
STD.DEV.	3.53	34	14.1	1.0	0.3287
LOW	3.30	18	15.3	73.4	0.1949
HIGH	17.50	159	56.2	76.9	1.3494

TABLE 9.5.6

LINEAR MODEL RESULTS

SITE: KTSC

352 OBSERVATIONS IN DATA SET: ELEC

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.1874	0.0030	0.0326	0.536	22.3	0.1072
L2	0.3470	0.0011	0.0041	0.534	22.4	0.1075
L3	0.3157	0.0022	0.0018	0.566	21.6	0.1037
L4	0.1486	0.0250	0.0319	0.527	22.5	0.1083
L5	0.3453	0.0071	0.0041	0.531	22.4	0.1078
L6	0.2928	0.0170	0.0018	0.559	21.8	0.1045
L1A	0.1187	0.0044	0.0358	0.926	29.8	0.1081
L2A	0.1187	0.0068	0.0054	0.904	33.8	0.1226
L3A	0.1187	0.0072	0.0023	0.916	31.7	0.1149
L4A	0.1187	0.0294	0.0327	0.925	29.9	0.1083
L5A	0.1187	0.0437	0.0047	0.917	31.4	0.1138
L6A	0.1187	0.0452	0.0020	0.926	29.8	0.1080

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	6.13	172	42.2	73.8	0.4825
STD.DEV.	3.97	88	11.4	1.9	0.1576
LOW	0.00	43	24.5	70.0	0.2017
HIGH	19.90	330	89.0	80.6	1.0716

TABLE 9.5.7

LINEAR MODEL RESULTS

SITE: ETSC

265 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms errors A/C
L1	0.0531	0.0095	0.0140	0.467	26.1	0.1275
L2	0.1002	0.0091	0.0023	0.447	26.6	0.1299
L3	0.0910	0.0094	0.0009	0.453	26.5	0.1292
L4	-0.2170	0.1042	0.0134	0.467	26.1	0.1276
L5	-0.1641	0.1006	0.0022	0.450	26.6	0.1295
L6	-0.1786	0.1036	0.0008	0.453	26.5	0.1292
L1A	0.1187	0.0081	0.0125	0.902	34.7	0.1287
L2A	0.1187	0.0087	0.0022	0.900	35.1	0.1300
L3A	0.1187	0.0088	0.0008	0.901	34.9	0.1294
L4A	0.1187	0.0530	0.0109	0.886	37.4	0.1385
L5A	0.1187	0.0558	0.0022	0.888	37.1	0.1375
L6A	0.1187	0.0568	0.0008	0.887	37.3	0.1380

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	5.05	123	33.5	72.2	0.4906
STD.DEV.	3.84	79	10.9	2.0	0.1750
LOW	0.00	5	16.6	67.7	0.1318
HIGH	17.50	329	66.3	77.6	1.1450

TABLE 9.5.8

LINEAR MODEL RESULTS

SITE: ETSC

91 OBSERVATIONS IN DATA SET: GAS

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.3809	0.0017	0.0166	0.116	22.4	0.1199
L2	0.5560	-0.0005	0.0005	0.008	23.8	0.1270
L3	0.4187	0.0016	0.0015	0.129	22.3	0.1189
L4	0.3141	0.214	0.0165	0.115	22.5	0.1139
L5	0.5774	-0.0066	0.0005	0.008	23.8	0.1270
L6	0.3547	0.0205	0.0015	0.129	22.3	0.1190
L1A	0.1187	0.0066	0.0236	0.922	29.5	0.1240
L2A	0.1187	0.0085	0.0017	0.900	33.3	0.1399
L3A	0.1187	0.0077	0.0021	0.920	29.8	0.1251
L4A	0.1187	0.0486	0.0189	0.926	28.7	0.1206
L5A	0.1187	0.0598	0.0010	0.913	31.2	0.1311
L6A	0.1187	0.0545	0.0017	0.927	28.6	0.1201

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	5.21	104	27.8	72.8	0.5433
STD.DEV	2.80	83	6.2	1.5	0.1282
LOW	0.30	10	16.6	68.9	0.3463
HIGH	12.20	263	43.0	77.2	0.9513

TABLE 9.5.9

LINEAR MODEL RESULTS

SITE: ETSC

174 OBSERVATIONS IN DATA SET: ELEC

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.0059	0.0113	0.0116	0.579	26.7	0.1224
L2	0.0369	0.0109	0.0027	0.600	26.0	0.1196
L3	0.0393	0.0111	0.0007	0.566	27.1	0.1245
L4	-0.2796	0.1173	0.0113	0.557	27.4	0.1259
L5	-0.2416	0.1136	0.0028	0.582	26.6	0.1223
L6	-0.2428	0.1158	0.0007	0.544	27.8	0.1276
L1A	0.1187	0.0087	0.0094	0.895	37.2	0.1273
L2A	0.1187	0.0089	0.0026	0.903	35.7	0.1223
L3A	0.1187	0.0092	0.0006	0.896	37.1	0.1269
L4A	0.1187	0.0534	0.0091	0.863	42.5	0.1454
L5A	0.1187	0.0540	0.0028	0.875	40.6	0.1391
L6A	0.1187	0.0560	0.0007	0.866	42.0	0.1439

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	4.97	133	36.5	71.9	0.4631
STD.DEV.	4.30	76	11.6	2.1	0.1896
LOW	0.00	5	18.1	67.6	0.1318
HIGH	17.50	329	66.3	77.6	1.1450

TABLE 9.5.10

LINEAR MODEL RESULTS

SITE: HTSG

179 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.5109	0.0087	0.0347	0.097	40.0	0.3294
L2	0.6412	0.0070	0.0028	0.095	40.0	0.3297
L3	0.5993	0.0080	0.0028	0.1075	39.8	0.3275
L4	0.4708	0.0528	0.0315	0.073	40.5	0.3338
L5	0.6049	0.0415	0.0027	0.076	40.5	0.3332
L6	0.5508	0.0489	0.0026	0.086	40.2	0.3313
L1A	0.1187	0.0196	0.0679	0.803	49.7	0.3517
L2A	0.1187	0.0266	0.0057	0.7481	56.1	0.3975
L3A	0.1187	0.0250	0.0056	0.771	53.5	0.3790
L4A	0.1187	0.1141	0.0494	0.813	48.4	0.3425
L5A	0.1187	0.1429	0.0041	0.796	50.6	0.3580
L6A	0.1187	0.1360	0.0040	0.805	49.3	0.3493

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	4.41	203	74.1	66.1	0.8307
STD.DEV.	3.02	79	11.3	1.8	0.3476
LOW	0.00	9	22.8	62.4	0.3240
HIGH	16.60	345	74.3	71.2	2.2892

TABLE 9.5.11

LINEAR MODEL RESULTS

SITE: HSLG

157 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.2612	0.0026	0.0159	0.211	23.0	0.0969
L2	0.3452	0.0020	0.0010	0.172	23.6	0.0993
L3	0.3143	0.0025	0.0009	0.226	22.8	0.0960
L4	0.2205	0.0223	0.0154	0.202	23.1	0.0974
L5	0.3057	0.0181	0.0010	0.169	23.6	0.0994
L6	0.2695	0.0222	0.0009	0.219	22.9	0.0964
L1A	0.1187	0.0060	0.0223	0.902	33.3	0.1017
L2A	0.1187	0.0088	0.0016	0.873	38.1	0.1159
L3A	0.1187	0.0082	0.0013	0.890	33.4	0.1079
L4A	0.1187	0.0386	0.0178	0.909	32.3	0.0984
L5A	0.1187	0.0515	0.0125	0.899	33.9	0.1034
L6A	0.1187	0.0487	0.0010	0.908	32.5	0.0990

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	5.59	154	41.1	70.2	0.4255
STD.DEV.	3.36	67	8.5	0.7	0.1095
LOW	0.20	10	27.4	68.1	0.2323
HIGH	20.70	360	63.3	71.9	0.7984

TABLE 9.5.12

LINEAR MODEL RESULTS

SITE: SRSG

226 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.2804	0.0042	0.0018	0.273	37.0	0.1503
L2	0.2836	0.0042	0.0002	0.272	37.0	0.1503
L3	0.2839	0.0044	-0.0001	0.272	37.1	0.1504
L4	0.2442	0.0302	0.0040	0.220	38.3	0.1556
L5	0.2509	0.0031	0.0005	0.219	38.4	0.1558
L6	0.2467	0.0336	0.0000	0.214	38.5	0.1563
L1A	0.1187	0.0067	0.0094	0.731	60.9	0.1760
L2A	0.1187	0.0079	0.0002	0.721	62.1	0.1793
L3A	0.1187	0.0081	0.0000	0.721	62.1	0.1793
L4A	0.1187	0.0501	0.0051	0.762	57.3	0.1656
L5A	0.1187	0.0544	0.0001	0.759	57.7	0.1664
L6A	0.1187	0.0556	0.0000	0.759	57.7	0.1664

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	4.83	160	47.8	74.2	0.4085
STD.DEV.	4.17	66	19.6	5.1	0.1766
LOW	0.00	19	20.4	64.9	0.1217
HIGH	18.60	317	80.9	84.5	1.0253

TABLE 9.5.13

LINEAR MODEL RESULTS

SITE: PAEG

90 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.6053	0.0042	0.0177	0.064	22.9	0.1853
L2	0.6790	0.0036	0.0016	0.031	23.2	0.1885
L3	0.6512	0.0037	0.0020	0.061	22.9	0.1855
L4	0.4733	0.0475	0.0178	0.064	22.9	0.1853
L5	0.5671	0.0404	0.0016	0.030	23.3	0.1886
L6	0.5342	0.0421	0.0020	0.061	22.9	0.1855
L1A	0.1187	0.0153	0.0327	0.921	29.4	0.2058
L2A	0.1187	0.0186	0.0022	0.910	31.4	0.2188
L3A	0.1187	0.0176	0.0029	0.915	30.5	0.2128
L4A	0.1187	0.1040	0.0217	0.933	27.1	0.1889
L5A	0.1187	0.1153	0.0015	0.929	27.0	0.1946
L6A	0.1187	0.1107	0.0022	0.932	27.3	0.1908

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	3.91	192	37.8	73.4	0.8246
STD.DEV.	2.23	75	7.2	0.0	0.1926
LOW	0.00	45	28.1	73.4	0.4110
HIGH	8.30	319	57.8	73.4	1.5294

TABLE 9.5.14

LINEAR MODEL RESULTS

SITE: OAMG

39 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	0.6867	-0.0024	-0.0209	0.097	30.5	0.1505
L2	0.5386	0.0010	-0.0019	0.100	30.5	0.1503
L3	0.6590	-0.0027	-0.0021	0.129	30.0	0.1478
L4	0.7267	-0.0211	-0.0203	0.096	30.6	0.1506
L5	0.5132	0.0101	-0.0020	0.101	30.5	0.1502
L6	0.7093	-0.0241	-0.0021	0.129	30.0	0.1478
L1A	0.1187	0.0121	0.0139	0.829	45.7	0.1759
L2A	0.1187	0.0144	0.0002	0.813	47.9	0.1839
L3A	0.1187	0.0135	0.0010	0.820	47.0	0.1803
L4A	0.1187	0.0769	0.0014	0.851	42.7	0.1639
L5A	0.1187	0.0836	-0.0011	0.855	42.1	0.1678
L6A	0.1187	0.0799	-0.0002	0.851	42.6	0.1638

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	5.40	170	46.3	71.3	0.5130
STD.DEV.	2.87	76	7.7	0.0	0.1605
LOW	0.10	46	35.0	71.3	0.2346
HIGH	10.50	319	62.1	71.3	0.8008

TABLE 9.5.15

LINEAR MODEL RESULTS

SITE: KAWG

30 OBSERVATIONS IN DATA SET: TOTAL

Model Identification	A	B	C	R^2	CV %	rms error A/C
L1	-0.2886	0.0113	0.0378	0.398	32.0	0.1390
L2	-0.0803	0.0101	0.0036	0.444	30.8	0.1336
L3	-0.1539	0.0116	0.0021	0.417	31.5	0.1368
L4	-0.7210	0.1406	0.0374	0.398	32.0	0.1390
L5	-0.4718	0.1262	0.0036	0.445	30.8	0.1335
L6	-0.6014	0.1447	0.0021	0.418	31.5	0.1367
L1A	0.1186	0.0032	0.0293	0.852	45.0	0.1473
L2A	0.1186	0.0056	0.0034	0.874	41.6	0.1361
L3A	0.1186	0.0055	0.0019	0.864	43.2	0.1412
L4A	0.1186	0.0191	0.0305	0.847	45.9	0.1500
L5A	0.1186	0.0365	0.0034	0.867	42.7	0.1398
L6A	0.1186	0.0362	0.0018	0.856	44.5	0.1454

VARIABLE	VEL MPH	DIR DEG	DBT °F	THER °F	INF A/C
MEAN	7.19	235	29.7	71.8	0.4573
STD.DEV.	2.82	82	5.9	0.0	0.1833
LOW	3.30	113	23.3	71.8	0.1411
HIGH	14.70	316	42.1	71.8	0.9867

all of the models produced similar rms errors for each site. This can be interpreted to mean that the linear models, as a group, are essentially equal in their ability to predict air infiltration but fail to consistently predict accurate values. The obvious solution to this dilemma was to either change the linear models, by expanding the available terms, or to discard the linear model approach and develop a model based on physical arguments.

9.5.3 Formation of Physical Models

The philosophy adopted in the development of the physical models was to utilize as much basic theory as was currently available and develop any remaining portions based on the research completed on this project. The basic theory was extracted from the ASHRAE Guide [9.1] and the technical papers previously reviewed in Section 9.3. This basic theory has identified two major weather variables, temperature differences and wind effects in addition to crack lengths, orientation, wind breakers, door and window openings, exhaust fan operation and the effects of operating open flame combustion systems within the residence.

The primary motivation for shifting the emphasis from the linear models to physical models was to reduce the quantity of statistical regression coefficients required. Three coefficients were required in the linear models which complicates the application of that approach to a new residence. It was anticipated that the physical models would, at best, be completely deterministic from theory alone or require, at most, a single statistical regression coefficient which would hopefully be a constant for all residences within a limited range or at least a constant for a particular residence style.

The development of the physical models proceeded in a progressive path beginning with the weather variables and adding the subsequent terms in a stepwise procedure until a final model was developed. The final model was determined to be complete when the influence all of the variables had been evaluated and incorporated into the model according to their explanatory importance in predicting the measured air infiltration values.

The first variable considered in the physical model was the influence of temperature differences. The temperature difference is not a direct influence on air infiltration but the pressure differences created because of the differences in air density due to temperature differences was determined to be proportional to air infiltration as predicted by the following equation which is presented in the ASHRAE Guide [9.1] where:

$$\Delta P_T = 0.52 \times P \times h \times \frac{1}{T_o} - \frac{1}{T_i} \qquad (9.5.4)$$

Where:

ΔP_T = Theoretical pressure difference across enclosure due to chimney effect, inches of water

P = Absolute pressure, lb/in^2

h = Distance from neutral zone, or effective chimney height, ft. For purposes of this project, the following definitions of h were utilized: Two Story, h = 8 ft; Split Level, h = 6 ft; and for a Ranch, h = 4 ft.

T_o = Absolute temperature outside, °F

T_i = Absolute temperature inside, °F

The second variable was also associated with weather effects and identified as a pressure difference due to the wind. The wind pressure term was calculated by using the equation presented in the ASHRAE Guide [9.1] where:

$$\Delta P_W = \frac{0.2549}{T_o} \times Vel^2 \qquad (9.5.5)$$

$$0.2549 = \frac{14.7\ \frac{lb_f}{in^2} \times 27.6798\ \frac{inH_2O}{lb_f/in^2} \left(\frac{5280\ ft}{3600\ sec}\right)^2}{2 \times 53.35\ \frac{ft\text{-}lb}{lb°R} \times 32.17\ \frac{lbm\ ft}{lb_f\text{-}sec^2}}$$

Where:

ΔP_W = Theoretical pressure difference across enclosure due to wind effect, inches of water

Vel = Wind speed, miles per hour

The first approach was to add the pressure differences and determine a resultant pressure difference for use in Equation 9.3.16, which resulted in the following:

$$INFPI = C\left[\frac{0.2549}{T_o} x Vel^2 + 0.52 x P x h x \left(\frac{1}{T_o} - \frac{1}{T_i}\right)\right]^n \qquad (9.5.6)$$

C = Proportionally constant

n = Exponent of flow, between 1/2 and 1

This approach was an initial attempt but neglected numerous variables. Neglected in the above equation was the effect of various wind directions and the value of n was not experimentally determined. As an initial assumption, the value of n was assumed to be equal to 1/2 based on two arguments. First, the flow was assumed to be turbulent and second, the flow through any opening is proportional to the square root of the sum of the heads acting on that opening.

A second attempt included a procedure to account for the orientation and various crack lengths on the four exposures and took the following form:

$$INFP2 = \beta_o(C_F \cdot \Delta P_F + C_B \cdot \Delta P_B + C_L \cdot \Delta P_L + C_R \cdot \Delta P_R) \qquad (9.5.7)$$

Where:

β_o = Statistical regression constant

$C_{F,B,L,R}$ = Equivalent crack lenghts on the Front, Back, Left, and Right surfaces of the structure, ft

ΔP_i = Theroetical pressure difference across Front, Back, Left and Right srufaces of the structure, inches of water

$$\Delta P_i = \frac{0.2549}{T_o} x Vel_i^2 + 0.52xPxhx \quad \frac{1}{T_o} - \frac{1}{T_i}$$

Vel_i = Normal velocity to surface, zero otherwise, miles per hour

i = Index for surface, Front, Back, Left, Right

The wind direction concept was developed into the above equation by defining the velocity term to be the normal component to a particular surface. Thus, the average wind direction can only be normal to a maximum of two adjacent surfaces during the hour. The wind pressure components on the remaining surfaces were assumed to be zero. This definition was then applied to all four exposures of a residence by assuming that the flow predicted through each exposure was additive.

Associated with the normal velocity component on each exposure is a characteristic opening or crackage related to the windows, doors, wall areas, and sills. The equivalent crack lengths are presented in Table 9.5.16 and the procedure used to determine the values is presented in Appendix 9B. The procedure employed to calculate the equivalent crack lengths was adopted from the crack method presented in the ASHRAE Guide [9.1]. The length of each crack was multiplied by the appropriate air infiltration factor and the sum was divided by the factor for non-weather stripped, average fit, double hung, wood windows. Thus, the equivalent crack lengths can be compared directly to determine the relative differences between exposures.

The second attempt neglected interaction effects of the wind on adjacent surfaces but the third model included those terms in the following form:

TABLE 9.5.16

EQUIVALENT CRACK LENGTHS
(ft)

(Normalized to non-weatherstripped, average fit double hung, wood windows)

Site	Location	Front	Back	Left	Right	Total
CTSE KTSC ETSC HTSG	Basement	17.31	30.2	20.2	34.8	102.5
	Conditioned	176.1	156.5	--	--	332.6
	Total	193.4	186.7	20.2	34.8	435.1
HSLG	Basement	15.1	22.4	20.3	--	57.8
	Conditioned	158.6	162.0	--	58.7	379.3
	Total	173.7	184.4	20.3	58.7	437.1
SRSG	Basement	--	--	15.7	--	15.7
	Conditioned	148.5	133.5	88.8	54.1	424.9
	Total	148.5	133.5	104.5	54.1	440.8
KAWG	Basement	27.2	26.4	--	10.1	63.7
	Conditioned	102.9	45.7	--	--	148.6
	Total	130.1	72.1	--	10.1	212.3
OAMG	Basement	27.2	26.4	--	--	53.6
	Conditioned	102.9	45.7	--	--	148.6
	Total	130.1	72.1	--	--	202.2
PAEG	Basement	27.2	26.4	10.1	--	63.7
	Conditioned	102.9	45.7	--	--	148.6
	Total	130.1	72.1	10.1	--	212.3

$$INFP3 = \beta_o[C_F \cdot \Delta P_F + C_B \cdot \Delta P_B + C_L \cdot \Delta P_L + C_R \cdot \Delta P_R$$
$$+ (C_F + C_L)\Delta P_F \Delta P_L + (C_F + C_R)\Delta P_F \Delta P_R$$
$$+ (C_B + C_L)\Delta P_B \Delta P_L + (C_B + C_R)\Delta P_B \Delta P_R] \quad (9.5.8)$$

In each of the preceeding models, a consistency in β_o was desired but not found thus becoming the impetus for the succeeding model.

The fourth model was developed as a simplification of the third model and only included the interaction effects which appears as:

$$INFP4 = \beta_o[(C_F + C_L)\Delta P_F \Delta P_L + (C_F + C_R)\Delta P_F \Delta P_R$$
$$+ (C_B + C_L)\Delta P_B \Delta P_L + (C_B + C_R)\Delta P_B \Delta P_R] \quad (9.5.9)$$

Again, a wide range of β_o for the various sites suggested that additional models be investigated.

Next, a generalized approach of the previous models, three and four, was investigated by regression to determine the equivalent crack length on each surface. The objective was to determine whether consistent equivalent crack lengths could be predicted for similar residences. Thus model five had the following form:

$$INFP5 = \beta_1 \cdot \Delta P_F + \beta_2 \cdot \Delta P_B + \beta_3 \cdot \Delta P_L + \beta_4 \cdot \Delta P_R + \beta_5 \cdot \Delta P_F \Delta P_L + \beta_6 \cdot \Delta P_F \Delta P_R$$
$$+ \beta_7 \cdot \Delta P_B \Delta P_L + \beta_8 \cdot \Delta P_B \Delta P_R \quad (9.5.10)$$

By a similar argument, model six was:

$$INFP6 = \beta_1 \cdot \Delta P_F \Delta P_L + \beta_2 \cdot \Delta P_F \Delta P_R + \beta_3 \cdot \Delta P_B \Delta P_L + \beta_4 \cdot \Delta P_B \Delta P_R \quad (9.5.11)$$

Observation of the results of the above models resulted in the decision to investigate the concept that the air infiltration was dependent upon the front crack lengths rather than the sides or back. The seventh model was:

$$INFP7 = \beta_o [C_T \cdot \Delta P_F + 2/3 \cdot C_T \cdot (\Delta P_B + \Delta P_L + \Delta P_R)] \quad (9.5.12)$$

C_T = Total equivalent crack length for the residence obtained by summation of all four exposures $C_F + C_B + C_L + C_R$

A more generalized approach was investigated in the next model:

$$INFP8 = \beta_o \cdot C_T \cdot \sqrt{\Delta P_T + \Delta P_W} \quad (9.5.13)$$

Where ΔP_T and ΔP_W apply to the entire residence and the wind direction is not considered or vectored to appropriate surfaces. The failure of the previous models, which included wind directional effects, was the primary motivation to drop the directional concept. The results indicated that the air infiltration could not be analyzed by considering wind directional components as originally thought but that air infiltration occurs in a more general pattern which can be characterized in these simpler models.

An alternative to model P8 was to consider the concept of the exponent n being equal to two-thirds instead of the square root which produced:

$$INFP9 = \beta_o \cdot C_T \cdot (\Delta P_T + \Delta P_W)^{2/3} \quad (9.5.14)$$

The results of models P8 and P9 indicated that the dependence or interaction between the temperature and wind effects was not equal but more dependent on approximately a 4:1 or 4:2 ratio. These ratios can be theoretically formed by considering that air infiltration, due to temperature effects, occurs through all four exposures while the wind could only influence one or at most two exposures simultaneously. An an initial estimate, a value of 1.5 was selected. This approach should be weighted according to the equivalent crack lengths on each exposure but the experimental measurements were not sufficiently detailed to allow the in depth analysis. Using these arguments, the equations were modified to:

$$INFP10 = \beta_o \cdot C_T \cdot \sqrt{4 \cdot \Delta P_T + 1.5 \cdot \Delta P_W} \quad (9.5.15)$$

and

$$INFP11 = \beta_o \cdot C_T \cdot (4 \cdot \Delta P_T + 1.5 \cdot \Delta P_W)^{2/3} \quad (9.5.16)$$

By now, some definite trends had been established in the regression results that indicated these last two models, P10 and P11, were sufficient in their ability to predict air infiltration rates as accurately as any previous model and in some cases resulted in an improvement.

One remaining modification was to adjust the ratio between the temperature and wind effects from 1.5 to $\sqrt{2}$ based on the theoretical consideration that the maximum resultant condition of a unit wind velocity on two adjacent surfaces. Finally, the previous results between models P10 and P11 indicated that both were essentially equal in their ability to predict the measured air infiltration rates, so from a theoretical justification the value of n = 1/2 was selected to be used in the final air infiltration model which is:

$$INFP12 = \beta_o \cdot C_T \cdot \sqrt{4 \cdot \Delta P_T + \sqrt{2} \cdot \Delta P_W} \qquad (9.5.17)$$

Where β_o was determined as a statistical regression coefficient but was essentially a constant for any given residence style. The β_o contains an estimate of the equivalent crack widths for the various residences. Another way of visualizing β_o is to consider it a factor which accounts for the "quality" of the workmanship in the construction of the residence.

All of the physical models presented have only included weather variables as the independent parameters. Three remaining parameters were investigated to determine their significance. Door openings and exhaust fan operation were included in the previous twelve physical models by the total amount of time that each was utilized during any hour. The third parameter investigated was gas consumption to the water heaters, dryers and central, warm air furnaces for any hour. Again, the gas consumption was included where appropriate in all twelve physical models along with the other parameters. The addition of these three parameters resulted in the following equation:

$$INFP13 = \beta_o \cdot C_T \cdot \sqrt{4 \cdot \Delta P_T + \sqrt{2} \cdot \Delta P_W} + \beta_1 \cdot \text{Door} \cdot \text{Normal Wind Velocity} + \beta_2 \cdot \text{Exh. Fan} + \beta_3 \cdot \text{Comb} \quad (9.5.18)$$

Analysis of the results at this level were further investigated by residual plots to identify possible second order effects or cross correlation terms.

A startling result was observed in the residual plots. The primary result was the appearance of auto correlation within the measured data and the simultaneous absence of suspected second order effects and cross correlation terms. The auto correlation was observed at each site and consequently attributed to the instrumentation of the automated air infiltration measuring device. The auto correlation was then included as an additional parameter in the twelve physical models. The auto correlation was modeled as a straight line for each time period of data that was measured at a residence. Thus, the order of the auto correlation varied between residences depending upon the number of time periods that measured data was collected.

Adding the auto correlation term, machine effects, to the door openings, exhaust fan operation and combustion effects resulted in the full equation:

$$INFP14 = \beta_o \cdot C_T \cdot \sqrt{4 \cdot \Delta P_T + \sqrt{2} \cdot \Delta P_W} + \beta_1 \cdot \text{Door} \cdot \text{Normal Wind Velocity} + \beta_2 \cdot \text{Exh. Fan} + \beta_3 \cdot \text{Comb} + \sum_{i=1}^{n} \beta_i \cdot C_i + M_i \quad (9.5.19)$$

Where:

$$\sum_{i=1}^{n} \beta_i \cdot C_i + M_i = \text{Machine Effects}$$

β_i = Statistical regression coefficient

C_i = Index for time period

M_i = Slope of regression line

This completes the formation of the physical models as presented in Equaltions 9.5.17-19.

The final analysis of these three models is presented in Section 9.5.4 as a separate topic but the development of the models to this level was very dependent upon the intermediate results of each step in the model building process.

9.5.4 Analysis of Physical Models

As a preliminary step to the analysis, a brief review of the measured data will be presented to illustrate the ranges and limitations of the independent variables. The average velocity of the wind was 5.25 mph with a maximum of 20.7 mph. The mean dry-bulb temperature outdoors was 45.5°F with a low of 15.3°F and a high of 92.4°F. Measured air infiltration rates ranged from 15 cfm to 489 cfm with a mean of 96.4 cfm. Exhaust fan operation was observed to obtain a maximum time on of 56.1 minutes with an average of 0.37 minutes. Finally, the maximum gas consumption rate was 95.3 cubic feet per hour with an average of 22.6 cubic feet per hour. Included in Appendix 9C is a graphical summary of these ranges. The measured air infiltration rates for each site was plotted as a function of the respective mean indoor-outdoor temperature differences and the average wind speed. On each plot, the standard deviation of each variable was utilized as the criteria to establish an enclosed area representative of the weather conditions that existed during the time periods when measured air infiltration data was being collected. The maximum wind speed was also included to identify the upper limit of the measured data. A composite of all the sites is presented in Figure 9.5.4.

A summary of the statistical results of the physical models P12, P13 and P14 is presented in Tables 9.5.17 - 9.5.19. The detailed statistical results for each site are presented in Appendix 9D. The remaining analysis consists of interpretation of these statistical results.

The first observation to be made from the inspection of the statistical results is that the accuracy, rms error, of the physical models is approximately equivalent to that obtained from the linear models. In some instances, the linear models did produce a smaller rms error relative to the physical models but the improved general applicability of the physical models completely overshadows the small rms error penalty.

A second observation from the statistical results is the relative stability of the regression coefficients for particular models. The maximum range of model P12 for similar style residences is 2.3 to 1 which is considerably

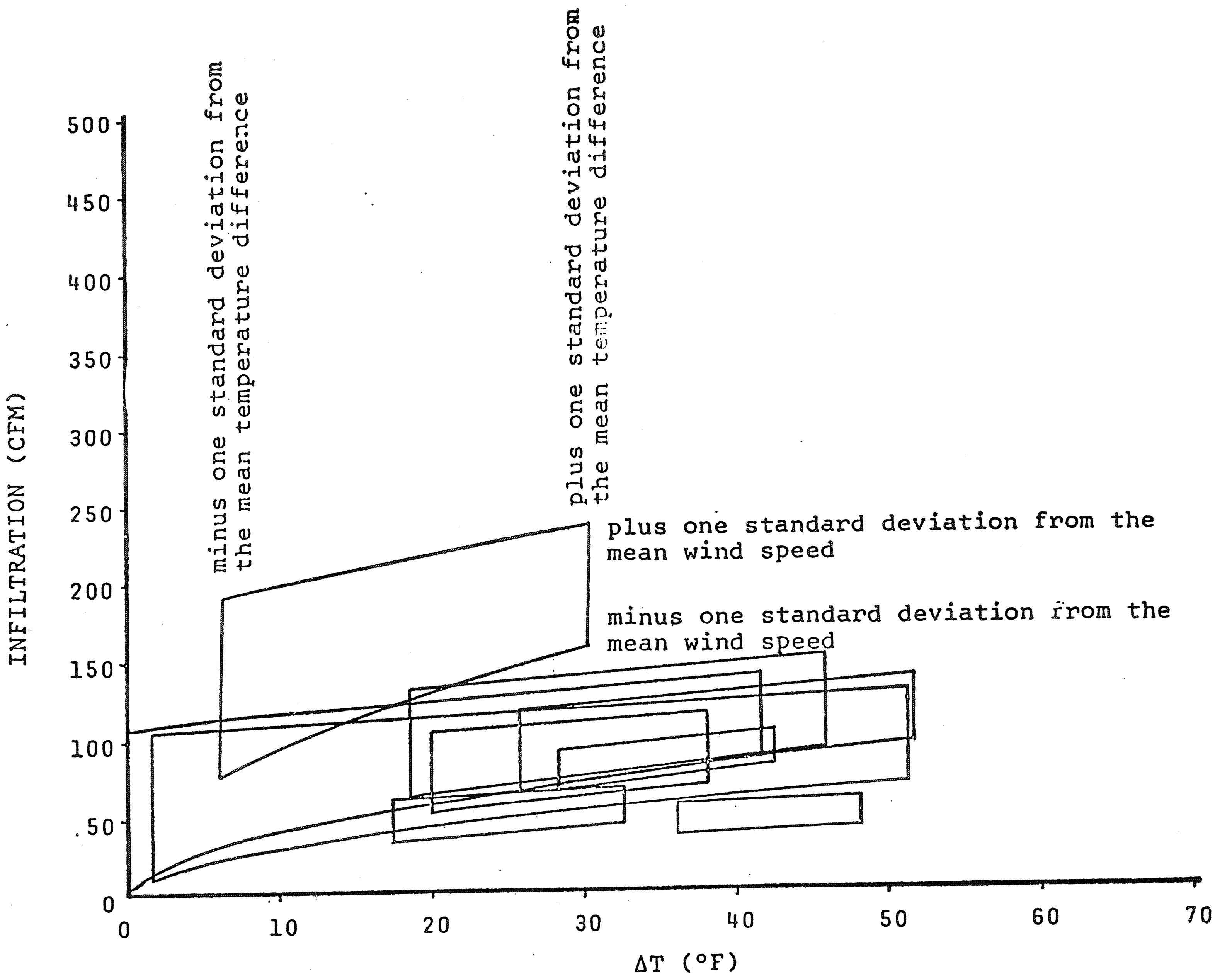

FIGURE 9.5.4: COMPOSITE OVERLAY OF THE MEASURED DATA RANGES

TABLE 9.5.17

STATISTICAL RESULTS OF PHYSICAL MODEL P12

Site	β_o	r^2	CV%	rms error A/C	No. Observ.
KTSC-Gas	1.42	0.905	34.4	0.2362	37
KTSC-Elec	1.26	0.958	21.6	0.1041	352
ETSC-Gas	1.36	0.950	23.1	0.1250	91
ETSC-Elec	1.21	0.882	37.1	0.1715	174
CTSE	1.29	0.949	25.8	0.1036	504
HTSG	2.77	0.839	43.6	0.3610	179
HSLG	0.96	0.916	30.0	0.1270	157
SRSG	1.04	0.728	56.9	0.2321	226
KAWG	1.14	0.913	32.1	0.1445	30
OAMG	1.57	0.845	41.7	0.2112	39
PAEG	2.65	0.941	25.0	0.2052	90

TABLE 9.5.18

STATISTICAL RESULTS OF PHYSICAL
MODEL P13

Site	β_o	β_1	β_2	β_3	r^2	CV%	rms error A/C	No. Observ.
KTSC-Gas	1.77	-36.69	3.58	-1.79	0.946	27.0	0.1775	37
KTSC-Elec	1.25	3.03	-0.02	0.00	0.958	21.6	0.1044	352
ETSC-Gas	1.37	-0.08	0.00	0.00	0.951	22.9	0.1229	91
ETSC-Elec	1.23	-0.30	0.00	0.00	0.888	36.4	0.1676	174
CTSE	NOT APPLICABLE - UNOCCUPIED							
HTSG	2.77	0.94	-3.28	0.00	0.843	43.4	0.3572	179
HSLG	0.85	-0.04	0.42	0.69	0.927	28.2	0.1183	157
SRSG	0.71	1.34	9.71	0.84	0.775	52.1	0.2111	226
KAWG	NOT AVAILABLE							
OAMG	NOT AVAILABLE							
PAEG	NOT AVAILABLE							

TABLE 9.5.19

STATISTICAL RESULTS OF PHYSICAL MODEL P14

Site	β_0	β_1	β_2	β_3	Machine Effects	r^2	CV%	rms error A/C	No. Observ.
KTSC-Gas	2.19	-66.14	4.38	-0.64	1	0.964	22.7	0.1448	37
KTSC-Elec	1.15	2.25	0.19	0.00	4	0.968	19.2	0.0910	352
ETSC-Gas	0.74	-0.02	0.00	0.00	1	0.965	19.7	0.1049	91
ETSC-Elec	0.42	-0.15	0.00	0.00	4	0.946	25.9	0.1166	174
CTSE	0.84	0.00	0.00	0.00	6	0.980	16.6	0.0657	504
HTSG	1.24	0.72	-1.01	0.00	2	0.875	39.1	0.3184	179
HSLG	0.37	-0.08	-0.34	0.17	2	0.954	22.7	0.0967	157
SRSG	0.17	0.83	8.29	0.58	3	0.912	33.0	0.1318	226
KWAG			-NOT AVAILABLE						
OAMG			-NOT AVAILABLE						
PAEG			-NOT AVAILABLE						

less than the near 20 to 1 ratios of the linear models. This improved stability reinforces the exceptance and application of the physical model approach.

At this point a final physical model must be selected from among the three proposed. The criteria for selection of the final model was self conflicting. First, the model should be the most accurate in its capabilities to predict the measured air infiltration rates. Using this criteria, model P14 would be selected because the overall accuracy was best based on the highest r^2 values, minimum CV and rms errors. However, the increased complexity of model P14 relative to P12 and P13 became the second criteria.

Model P13 was slightly more accurate than P12 but again was more complex to implement. Thus, using the criteria of reduced complexity results in the selection of model P12. In order to resolve this dilemma, further investigation is required.

It is expected that any model will be improved as additional variables are added. Consequently, the question arises whether the improvement from model P12 to P13 and P14 is attributed to the fact that additional variables have been included or that the variables are indeed explanatory and statistically significant. Inspection of the results indicates that the answer is not clearly resolved. At certain sites, the additional variables in models P13 and P14 are not statistically significant as determined by F-ratio or t-ratio tests even though the overall model is more accurate.

A point of clarification is required as to the interpretation of the meaning of statistically significant. An example will best illustrate the meaning. Two of the variables included in model P13 relative to model P12 are the exhaust fan operation and door openings. When these two variables are determined to be statistically insignificant it only means for those specific conditions that were measured and included in the data for analysis. This does not imply that they may never be significant. It is a well known fact that air infiltration rates increase by a factor of 2-4 air changes if doors and windows are left open for an entire hour interval. A similar argument can be presented for continuous operation of an exhaust fan. The point is, that the duration of these events, as recorded in the measured data, were not of sufficient duration to become a statistically significant factor in some cases. This was expressed earlier with an average exhaust fan operation of 0.37 minutes. Even though the variable is not statistically significant over the entire data set and cannot be justified for inclusion into the model, it could be very significant for a particular hour but will still not be included.

A second argument arises concerning the distinction between models P12 and P13. The inclusion of the additional variables resulted in only a marginal improvement in model

P13 over P12 as interpreted by the r^2, CV and rms error values.

Based on the two preceeding arguments, model P13 was set aside and a comparison between P12 and P14 was completed. Without question, model P14 was a more accurate model, as determined by r^2, CV and rms error, but it suffered from increased complexity. Specification of up to ten regression coefficients would be impractical from the standpoint of implementation for the additional 5 to 15% increased accuracy. Therefore model P12 was selected as the final form of the air infiltration model.

The general characteristics of model P12 for various combinations of temperature differences, wind speeds, equivalent crack lengths and residences styles are presented in Figure 9.5.5. The entire range of air infiltration rates can be adjusted for the appropriate β_o to account for higher rates. At a specific site, the β_o can be interpreted as a factor which accounts for the workmanship of the construction. This is indeed a broad factor and could contain the potential for a large value but the statistical results of the measured data indicated a relatively stable value with a maximum range of 2-1/2 to 1. It appears that this factor allows for considerable approximation as to the accurate prediction capabilities of the model when applied to a non-research residence. This fact cannot be denied in the extreme case but the advantage is twofold. First, for seven of the nine

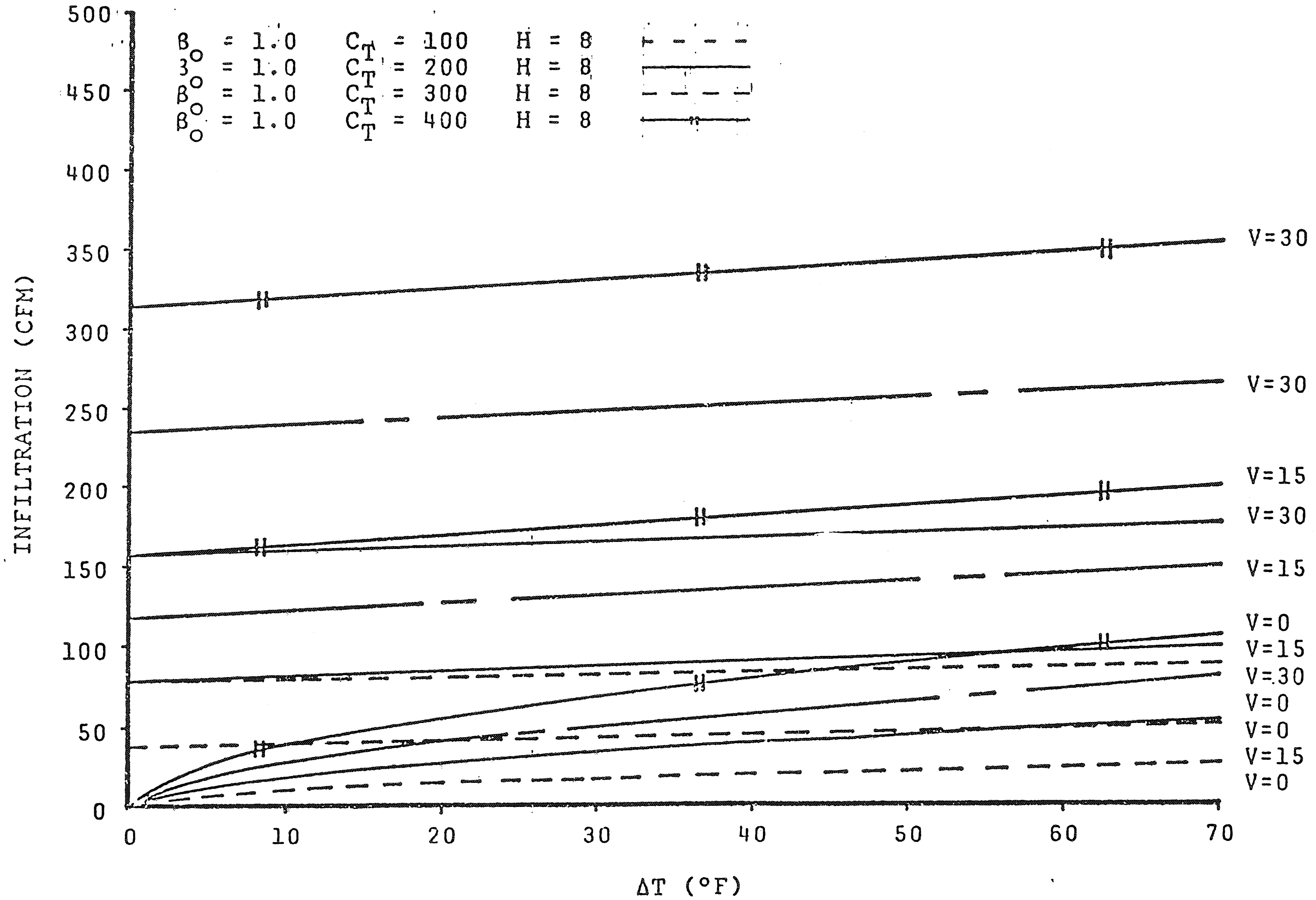

FIGURE 9.5.5: GENERAL CHARACTERISTICS OF MODE P12

sites, the range of β_o for similar residence styles was only 1.38 to 1 and 1.07 to 1. The relative stability of these ratios was very encouraging. Second, the model contains a procedure for the prediction of air infiltration rates under varying weather conditions which is absolutely essential for accurate load and energy analysis of a residence. These two facts support the advantage of this physical model approach relative to linear models.

Another advantage of the physical model, relative to the linear models, is the absence of a leading coefficient or constant. In the physical model, the predicted air infiltration rates become zero as the driving potentials go to zero. This was illustrated in Figure 9.5.5 where all the zero velocity lines pass through zero. An interesting question then arises relative to the investigation concerning the magnitude of the leading coefficient or intercept as presented on the linear models in Section 9.5.1 and Figures 9.5.1 and 9.5.2. For comparison purposes, the physical model was applied to the same weather conditions as was presented in Figure 9.5.1. Note that the temperature differences were only 3°F to 4°F as a minimum. A plot of the physical model is presented in Figure 9.5.6. The dashed line is a least squares straight line fit to the physical model for the same temperature difference range that was used in the linear model. The physical model when linearized produced an intercept of 0.1197 air changes which compares with the 0.1187 obtained

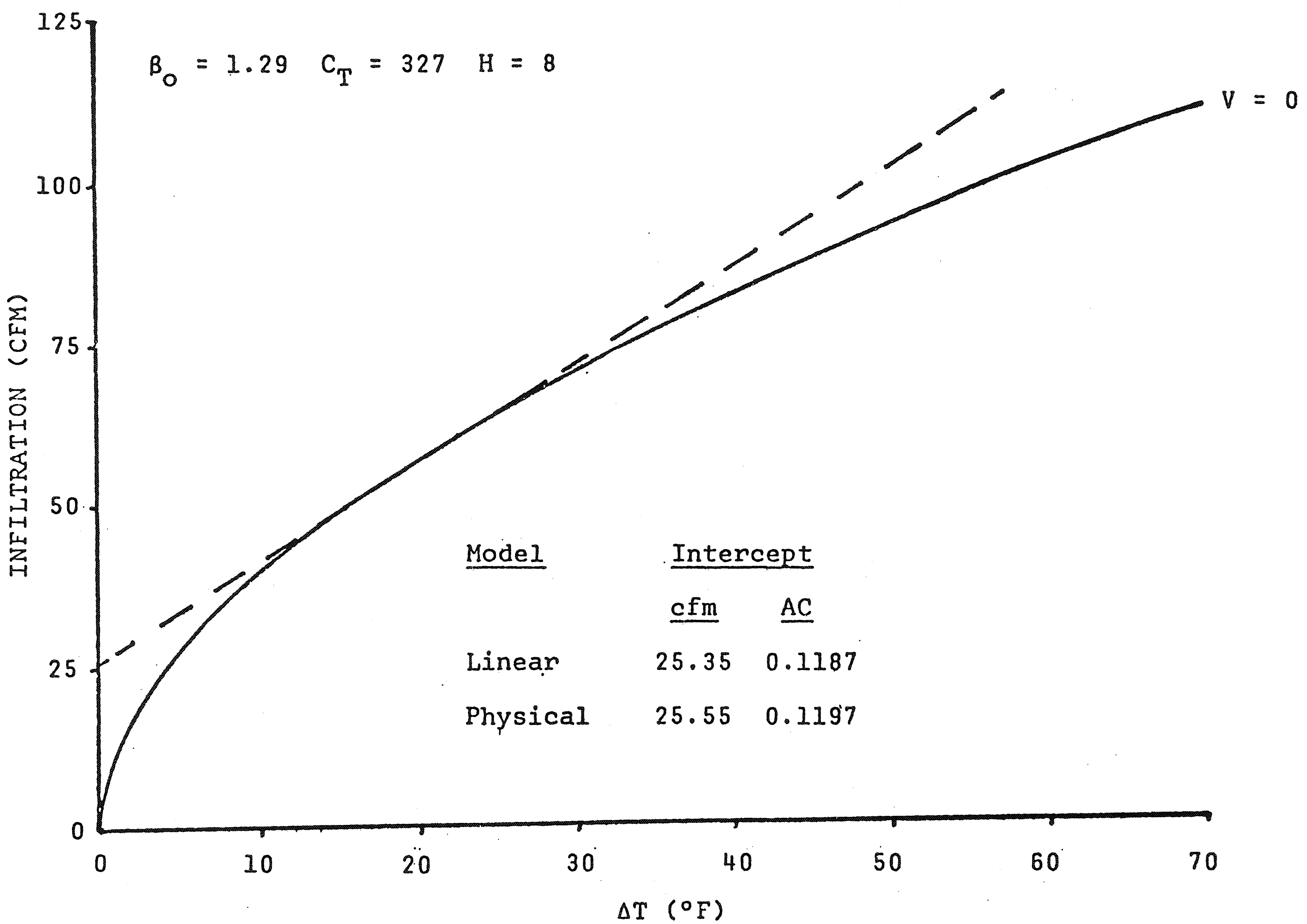

FIGURE 9.5.6: PHYSICAL VS LINEAR MODEL TEMPERATURE EFFORTS

in the linear model. Thus, the physical model predicts essentially the same air infiltration rates for the given temperature differences but then predicts zero air infiltration if the driving potentials become zero.

The last argument based on the physical model was the capability to distinguish the effects of combustion within a residence. Unique to this project was the changing of the heating systems in two residences from forced air gas furnaces to electric heating systems. During each period of the various systems operation, air infiltration rates were measured. Model P12 was then used to analyze the data and the results are presented in Table 9.5.17. The ratio of the β_o coefficient between the gas and electric systems for KTSC was 1.127 to 1 and 1.124 to 1 for ETSC. These ratios indicate that the air infiltration rates of the residences were 12.7% and 12.4% respectively higher with the gas system relative to the electric systems. This statement must be qualified due to the measurement procedures employed on this project. The air infiltration rates were only measured within the conditioned space of the residence, which excluded the basement, because the furnaces and ductwork were located in the basements. The basements were not considered as a part of the conditioned space because the space conditions were not maintained directly by the heating systems. Consequently, the air infiltration rates between the gas and electric systems may be further separated when the air infiltration rates into the basements are considered. The basement air infiltration rates have been considered, from an analysis procedure as opposed to direct field measurements, and the results are presented in Chapter 12.

Again, the relative consistency in the statistical regression coefficients for the gas heating systems, 1.42 and 1.36, indicate that the physical model is sufficient for use as a prediction model of air infiltration rates.

Comparisons of measured air infiltration rates and the results of model P12 for various seasons of the year are presented in Appendix 9E. Auxiliary plots at the top of each figure illustrate the hourly weather conditions that existed when the air infiltration rates were being measured. The deviations between the measured and simulated values are not as large as indicated on the plots because the measured data needs to be adjusted to account for the auto correlation due to the measuring device. This effect is clearly demonstrated in Figure 9.E.6 where the bottom simulated line was obtained from model P12 and the top simulated line include the auto correlation effects.

9.6 Results and Conclusions

The results of this research on air infiltration must be evaluated relative to two criteria. First, the results must be compared to the measured data to determine the applicability of the model and the resultant accuracy. As an extension to this concept, the model must also be evaluated for its ability to include the effects and interactions of all the parameters that were identified in the literature review, Section 9.3, as being significant. This criteria is absolute while the second criteria is relative to contemporary research results. The results of this research were based on the measured air infiltration rates of nine residences over a one year period. This fact is not impressive because numerous researchers have used one or more years but the significant difference is the quantity of measurements made during the year. Typically, the researchers have only obtained from 4 to 25 hours of data from 2 to 20 residences. As the number of residences increased, the quantity of measured data decreased. This is not intended to be a criticism of the previous research but just an observation which is easily understood because of the manual data acquisition system employed. Conversely, the automated procedure employed on this project was capable of measuring air infiltration rates continuously. This fact accounts for the solid 1879 hours of data collected on this project. Based on these two criteria, the results of this project are a significant improvement relative to previous research.

Although this research has made a contribution to the modeling of air infiltration rates it is not the final answer. Numerous assumptions were made during the development of the air infiltration model and each assumption could be either experimentally confirmed or denied.

Specific conclusions that can be stated from the research revolve around the results presented in the analysis of Section 9.5.4. The model accounts for indoor-outdoor temperature differences, wind speed, neutral zone, cracks, the interaction of temperature and wind effects, gas versus electric heating systems and evaluated exhaust fan operation and the effects of door openings as parameters in the prediction of air infiltration rates. Although this list is not complete it includes a majority of the parameters identified in the literature review.

The influence of gas heating systems relative to electric heating systems was a 12-1/2% increase in the air infiltration rates to the conditioned space. Further research is required to determine the magnitude of the differences in the air infiltration rates into the basements with the two different systems.

Finally, the conclusion must be stated that a computerized calculation procedure for the prediction of air infiltration rates into a residence with varying weather conditions has been completed. The results of this model can be utilized in the calculation of the load and energy requirements of a residence, which satisfies the original objective in performing this research.

9.7 Recommendations

The recommendations from this research fall into two areas. First would be improvements in the data acquisition procedures and second would be in the analysis.

The data acquisition procedure could be improved by developing a procedure to replace the strip chart recorder to expedite the data reduction procedure. A more significant improvement would be to incorporate the capability of increasing the sampling rate of the device. This would allow for a more detailed investigation of the short duration effects, such as door openings and exhaust fan operation.

From the analysis viewpoint, improvements could be realized if the air infiltration measurements were supplemented with simultaneous measurements of exterior and interior pressure differences and distributions, boundary layer wind effects, and interior air flow paths. These measurements should be on a time basis significantly shorter than the hourly intervals utilized on this project to determine whether the flow is steady-state or is characterized by pulsations and eddy flow.

Implementation of these recommendations would provide the researcher with the supporting data to analyze the assumptions made on this project and suggest the inclusion of additional term or interactions which would improve the model.

APPENDIX D

SUMMARY OF MODELS

APPENDIX D

PARTIAL LIST OF RESIDENTIAL MODELS

Source	Model	Open Window Correlation	Data Base	Comments
Dick/Thomas (G.B.)	$INF = A+BW+C(n+1.4_m) + D(n+1.4_m)$	yes	20 homes	n=mean # of open vents
Dick/Thomas (G.B.)	$INF = (A+B_n)\ W$ when $W^2/\Delta T > 3$ $INF = (C+D_n)\ (\Delta T)^{1/2}$ when $W^2/\Delta T < 3$	yes	8 homes	
Bahnfleth/Mosley/ and Harris (U.S.A.)	$INF = A+BW+C\Delta T$	no	2 homes	
Achenbach/Coblentz (U.S.A.)	$INF = A+BW+C\Delta T$	no	10 homes	
Laschober/Healy (U.S.A.)	$INF = A+BW_L + C\Delta T$ $INF = A'+B'W_L + C'\Delta T + D'\ EG$	no	2 homes	W_L = long side wind concept EG = +1,-1(gas or electric)
Taumra/Wilson (Canada)			2 homes	
Howard (Australia)	INF = f (wind velocity, chimney openings)	no	6 homes	
Elkins/Wensman (U.S.A.)	$INF = (A-B\theta)W$	no	2 homes	
Hunt/Burch (U.S.A.)	$INF = A + B\Delta T$ $INF = C\Delta T^{1/2}$	no	1 townhouse	Lab set up-no wind
Hittman Assoc. (U.S.A.)	$INF = A + BW + C\Delta T$	no		

Source	Model	Open Window Correlation	Data Base	Comments
Malik (U.S.A.)	$INF = A+B \cdot W \cdot \cos(\theta - \theta_o) + C\,\Delta T + DG + E \cdot B + F^* \cdot F$	no	2 townhouses	F: Front Door Opening B: Time Basement Door is open G: Gas Consumption
Hittman Assoc. (U.S.A.)	$INF = O.A.^* \, (A + B\,\Delta T + CW)^{.66}$	no	6 houses	O.A.= Orifice coefficience = $\frac{\text{orifice area}}{\text{room volume}}$
Hartman (Sweden)	$Z_e \cdot Z_b \cdot (A + B \cdot W/ + C\,\Delta T)$	yes		Occupancy factor, Z_b Corner coefficient, Z_e
Ohio State University (U.S.A.)	$INF + A + B(\Delta T) + C(Vel)$ $INF = A + B(\Delta T) + C(SF \cdot Vel)^2$ $INF = A + B(\Delta T) + C(Vel)^2$ $INF = A + B(\Delta T)^{1/2} + C(Vel)$ $INF = A + B(\Delta T)^{1/2} + C(SF \cdot Vel)^2$ $INF = A + B(\Delta T)^{1/2} + C(Vel)^2$ $INF = 0.1187 + B(\Delta T) + C(Vel)$ $INF = 0.1187 + B(\Delta T) + C(SF \cdot Vel)^2$ $INF = 0.1187 + B(\Delta T) + C(Vel)^2$ $INF = 0.1187 + B(\Delta T)^{1/2} + C(Vel)$ $INF = 0.1187 + B(\Delta T)^{1/2} + C(SF \cdot Vel)^2$ $INF = 0.1187 + B(\Delta T)^{1/2} + C(Vel)^2$	no	6 houses 3 apts.	SF: wind direction See Appendix C for statistical significance and correlation coefficients

Source	Model	Open Window Correlation	Data Base	Comments
Ohio State University (Cont'd.)	14 physically-based models in Appendix C: best according to authors $INF = B_o C_t \sqrt{4\ \Delta P_t + \sqrt{2}\ \Delta P_w}$			C_t: crack length

APPENDIX D (Cont'd)

COMMERCIAL BUILDINGS

Source	Model	Open Windows	Comments
Shaw-Tamura (Canada)	Stack: $Q_s = C_w S \left[0.52\ \gamma\ p \left(\frac{dt}{T_i T_o}\right)\right]^{nw} \frac{(B+1)^{n_w+1}}{n_w+1}$ Wind: $Q_m = 5.375 \times 10^{-4}\ \alpha\ C_w\ LH^{1.435}\ V_s^{1.30}$ Total: $Q_{LRG} = 1 + 0.24 \left[\frac{Q_{sml}}{Q_{lrg}}\right]\ 3.3$	1 per facade	See Appendix B
National Bureau of Standards (U.S.A.)	See Appendix B	no	Based on Sander/Tamura model
University of Glasgow (Scotland)	See Appendix B	?	Details unavailable
Construction Engineering Research Laboratory (U.S.A.)	$INF = INF_{design}$ x schedule x (A+BDT+CW)	no	Schedule based on occupancy; INF_{design} is inputted by user
International Heating & Ventilating Engineer (London)	NOMOGRAPHS	no	Design criteria primarily

APPENDIX E

COMMERCIAL BUILDING TEST RESULTS

FORM NBS-259
(3-63)

Appendix E

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF TEST

to

Energy Research and Development Administration

Air Exchange and Ventilation System Measurements in the Norris Cotton Federal Office Building in Manchester, New Hampshire

by

Charles M. Hunt
Thermal Engineering Section
Building Environment Division
Institute for Applied Technology

Summary

Air exchange rates and carbon dioxide levels were determined for the Norris Cotton Federal Office Building in Manchester, New Hampshire during the week of February 14-18, 1977.

Measured air exchange rates, averaged for the entire building, were of the order of 0.7 to 0.8 air changes per hour when the building's ventilation system was in the complete recirculation mode and 0.9 to 1.0 air changes per hour when the ventilating system for floors 4-7 was operated in the variable volume mode and introducing fresh outdoor air into the building.

Carbon dioxide concentrations of 875 to 2440 ppm per million were found on floors 4-7 when the central ventilation system was not operating and somewhat less when the system was operated with complete recirculation. Concentrations on floors 1-3 ranged from 675 to 875 ppm with complete recirculation. These levels are less than the OSHA standard of 5000 ppm for an 8-hour day or 2900 ppm implicit in the 5 cfm per person minimum outside air requirement in ASHRAE Ventilation Standard 62-73. However, some of these levels are higher than the CO_2 levels implicit in the ASHRAE recommended ventilation rate of 15-25 cfm per person for office space.

1. Introduction

The GSA Norris Cotton Federal Office Building in Manchester, New Hampshire has been designed and built to use a fraction of the energy required to heat, cool, and illuminate conventional buildings of similar size. Some of the energy saving features in the shell design include cubical shape to minimize surface to volume ratio, small window areas with double glazing, and no windows on the north side of the building. Many other energy conserving features are included in the building hardware and operation. The building is a demonstration unit and is equipped to continuously monitor and store various energy related parameters such as temperature, humidity, air and water flows, solar radiation, indoor illumination, and electric power and gas consumption.

The building was dedicated October 8, 1976, and during its first winter of operation has used more energy than was predicted. A comprehensive analysis of building performance is in progress. As a part of this analysis measurements were made of the combined amount of air coming into the building through leakage and through design ventilation. The sulfur hexafluoride (SF_6) tracer technique was used for the purpose. A description of the particular system used has been given previously [1, 2].

In addition to tracer measurements of ventilation, spot checks of carbon dioxide were made on each of the floors. During the week of February 14-18, 1977 when these measurements were made, the building was operating in the complete recirculation mode much of the time and in addition, the main ventilation system serving floors 4 through 7 was cut off entirely for a few days. This was done to maintain comfort in the building and it afforded an opportunity to measure carbon dioxide levels under conditions of restricted ventilation and compare them with the maximum level permitted by the OSHA standard or those predicted from the ASHRAE ventilation standard.

This letter report is preliminary in nature and confines itself to the ventilation aspects.

2. Description of the Ventilation System

Floors 1-3 and 4-7 of the building are served by separate ventilating systems. The main features of these systems are represented schematically in Figures 1A and 1B. These diagrams include only elements which control the main airflows to and from the building. Figure 2 is a more detailed diagram showing toilet exhausts and components of the HVAC system.

3. SF_6 Tracer Measurements

SF_6 was injected into the ventilating system immediately upstream from the return fans, F_2 and F_4 in Figures 1A and 1B respectively and it was monitored in the output of these fans. Amounts of the order of 100-120 ml for each system were required to establish initial concentrations slightly below 10 parts per billion in the ventilated space. In repeat runs, smaller amounts were injected to bring the concentration back to the desired starting level. Initially about an hour was allowed for the tracer to distribute and for the concentration decay rate to stabilize; thereafter about 10 minutes elapsed between the addition of a small increment of tracer and the start of measurements of concentration decay rate.

4. Air Exchange Rates

The ventilating systems were operated with the outside air dampers, D_1 and D_4 in Figures 1A and 1B, closed to obtain nominal 100 percent recirculation. This also required opening of dampers D_3 and D_6. In the first measurements, SF_6 was introduced only to the main ventilation system of floors 4-7. In this way any air rising from the lower floors due to the stack effect would be essentially free of tracer. It was felt that comparison of measurements obtained this way with measurements obtained with tracer distributed throughout the entire building would provide an approximate estimate of the relative amounts of air leakage to floors 4-7 from the outside and from the lower floors. The results after adding SF_6 to floors 4-7 are shown in columns A and B of Table 1. Tracer was then added to the entire building, and the results are shown in columns C and D of the table. Apparent infiltration rates of 0.65 and 0.79 air changes per hour were obtained for floors 4-7 when the air from the lower floors contained no tracer and 0.58 and 0.49 air changes per hour when tracer was introduced to the entire building. This suggests that approximately 0.1 to 0.2 air changes per hour was due to air rising from the lower floors.

The air leakage rates in floors 1-3 were higher than in the upper floors when operating in the nominal 100 percent recirculation mode*.

In the final tracer measurements, the outside air dampers to floors 4-7 were opened and operated in the variable volume mode. The dampers to floors 1-3 were not opened because of problems in supplying sufficient heat to these floors. Under these conditions, air exchange rates for the upper floors were higher than to the lower floors as might be expected. The results are shown in columns E and F of Table 1.

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* Actually the outside air dampers to floors 1-3 were not set in the closed condition but inspection indicated them to be closed.

The air leakage rates in floors 1-3 were lower when the outside air dampers to the upper floors were opened than when the whole building was operated nominally with 100 percent recirculated air. The reason for this apparent decrease is not known. It suggests that 1) possibly there was some unidentified leakage path from the upper to the lower floors, or 2) the building was operating under a slight negative pressure when all the outside air dampers are closed, and opening dampers raised this pressure to where it was more nearly equal to the outside pressure.

Weighted average air exchange rates for the entire building were calculated assuming that floors 1-3 represented 3/7ths of the building volume and floors 4-7 4/7ths. The results are shown in the bottom line of Table 1. Air exchange rates of the order of 0.7 to 0.8 changes per hour were obtained with complete recirculation and 0.9 to 1 air changes per hour with the upper floors operating in the variable volume mode. These estimates include air exchange due to toilet exhausts and possibly a special exhaust from the 4th floor as well as natural leakages. According to the ventilation design for the building, the combined toilet exhausts amount to 3968 cfm. This corresponds to 0.24 air changes per hour for a 1,000,000 ft^3 building. The exhaust from the medical examining room on the 4th floor is given as 1592 cfm or about 0.1 air changes per hour when averaged for the entire building.

The results of the above measurements are still being analyzed to determine what implications they have for the energy use in the building. As mentioned previously, during this first winter of operation, the building has used more energy than was originally predicted using a computer simulation and hour-by-hour weather data. However, the assumption used in the computer calculations was that the overall air change rate due to ventilation and natural air leakage would be constant year around and equal to 0.48 per hour.

5. Air Leakage From Basement

To determine how much air leaked into the building from the basement 200-220 ml of SF_6 was released in the basement and concentrations were monitored on the upper floors. Small increases in tracer concentration were observed on floors 1-3 and 4-7, but they were too small to be measured quantitatively under the conditions of the experiment. A slightly greater increase was observed in the penthouse near the elevator. This suggests that the elevator shaft is one of the leakage paths.

6. Carbon Dioxide Concentrations

Prior to making air exchange measurements described in the previous sections, the main ventilating system to floors 4-7 was shut down while adjustments were being made to the heating system. This afforded an opportunity to measure carbon dioxide levels in the building under conditions of restricted ventilation. Carbon dioxide is given off by people at a rate which is dependent on the level of activity. About 0.75 ft^3/hr per person has been offered as an estimate of typical output for adults not engaged in heavy work [3]. Carbon dioxide concentration in an occupied building can be used as an indicator of whether ventilation exists. The ASHRAE ventilation standard [4] recommends a minimum of 5 cfm outside air per person. This may be translated into about 2500 ppm CO_2 contributed to the ventilation air per person which added to the normal background level of CO_2, amounts to about 2900 ppm.

Air samples were collected on each floor in small balloons during the afternoon of February 15 and the morning of February 16. Sampling points were not selected to be representative for the entire floor, but samples were taken from the rooms containing the most people. This was to approximate maximum levels of CO_2. The results are shown in Tables 2 and 3. The highest level of CO_2 recorded in these measurements was 2400 ppm or about 5.5 times the measured outdoor level. This concentration was obtained in a room while several people were taking an examination.

At present there is no consensus as to the extent to which outside air may be restricted to save energy without jeopardizing indoor air quality. However, from the point of view of CO_2 alone, the building met the existing OSHA standard [5, 6] of 5000 ppm for an 8-hour exposure. It was also below the CO_2 level of about 2900 ppm implicit in the ASHRAE 5 cfm per person minimum ventilation requirement, but exceeded the levels implicit in the ASHRAE recommended rate of 15-25 cfm per person for office space. It should be noted that the ASHRAE standard was prepared before energy conservation became a recognized national priority.

It should also be noted that the highest levels of CO_2 were always observed on the 4th floor. As previously mentioned, there is a special exhaust of 1592 cfm from the 4th floor. This ventilates a medical examination room. The high CO_2 concentrations suggest that perhaps this exhaust was not operating during any of the CO_2 or tracer tests.

Carbon dioxide concentration may also be used to make an estimate of the air infiltration rate of the building. To do this, use is made of the relationship

$$c_\infty = c_o + \frac{G}{v}, \qquad (1)$$

or

$$v = \frac{G}{c_\infty - c_o}, \qquad (1a)$$

where

c_∞ = indoor concentration after infinite time*

c_o = concentration in outside air

G = rate of generation

v = rate at which outside air enters building

Table 4 shows the results of additional measurements made of CO_2 concentrations during the afternoon of February 17, 1977 with the ventilation system on and in the complete recirculation mode. The total number of people in the building at the time was estimated to be 277 and the average of the CO_2 levels listed is 881 ppm. Thus at a generation rate of 0.75 cfh per person

$$G = 277 \times 0.75 = 208 \text{ cfh}$$

$$c_o = 441 \times 10^{-6}$$

$$c_\infty \approx 881 \times 10^{-6}$$

and.

$$v = \frac{208}{(881 - 440) \times 10^{-6}} = 0.46 \times 10^{-6} \text{ cfh}$$

In a 1,000,000 ft^3 building this corresponds to 0.46 air changes per hour. This is less than the comparable air exchange rates given in Table 1 of 0.67 and 0.82 air changes per hour. However, the CO_2 samples were taken in the rooms with the most people to look for areas of inadequate ventilation. The average CO_2 level in the building was probably less than 881 ppm used in the calculation.

6. References

1. "Automated Instrumentation for Air Infiltration Measurements in Buildings", D. T. Harrje, et al, Center for Environmental Studies, Princeton, New Jersey, Report No. 13, April, 1975.

2. "A Prototype Semi-Automated System for Measuring Air Infiltration in Buildings Using Sulfur Hexafluoride as a Tracer", C. M. Hunt and S. J. Treado, National Bureau of Standards Technical Note 898, March, 1976.

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* It should be noted that in a building in which air recirculates at a rate equivalent to 5 air changes per hour a concentration greater than 99 percent of the ultimate concentration will be reached within an hour.

3. "Shelter Design and Analysis", Vol. 3 - "Environmental Engineering for Shelters", TR20-(Vol. 3), May 1969, p. 43, Department of Defense, Office of Civil Defense.

4. ASHRAE Standard 62-73, "Standards for Natural and Mechanical Ventilation", American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (1973).

5. Part 1910, "Occupational Safety and Health Standards", Federal Register 36, No. 157, Friday, August 13, 1971, p. 15102.

6. OSHA Workroom Air Standards G-1 and G-2, Federal Register 39, No. 125, Thursday, June 27, 1974.

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Project 4622411
May 23, 1977

Table 1 Air Exchange Rates in the Norris Cotton Federal Office Building in Manchester, New Hampshire, February 17, 1977[1]

Floors	Tracer Added Only to Floors 4-7		Air Changes Per Hour — Tracer Added to Whole Building: Main Fans On, Outside Dampers Closed		Air Changes Per Hour — Tracer Added to Whole Building: Main Fans On, Floors 4-7 Dampers VAV[2], Floors 1-3 Dampers Closed	
	A	B	C	D	E	F
1-3	-	-	1.13	0.92	0.81	0.79
4-7	0.65	0.79	.58	.49	1.13	1.05
Building Average	-	-	.82	.67	.99	.94

[1] Outside temperature 25° F at 6:00 p.m., 20° F at 7:00 p.m., wind velocity of order of 6 mi/hr.

[2] VAV = Variable Air Volume.

Table 2 Carbon Dioxide in Air Samples Taken From Various Floors in the Norris Cotton Federal Office Building, February 15, 1977, 3:00 to 5:00 p.m.[1]

Floor	No. of People on Floor	No. of People in Room Sampled	CO_2 ppm	Ratio Indoor / Outdoor CO_2 Concentration
1	-	-	-	-
2	48	30	700	1.6
3	32	9	675	1.5
4	17	4	1500	3.4
5	55	15	1250	2.8
6	60	17	1175	2.7
7	26	12	1225	2.8

[1] Main supply and return fans to floors 4-7 shut off. Main supply and return fans to floors 1-3 on with outside air dampers closed.

Table 3 Carbon Dioxide in Air Samples Taken From Various Floors in the Norris Cotton Federal Office Building, February 16, 1977, 10:30 to 12:00 a.m.[1]

Floor	No. of People on Floor	No. of People in Room Sampled	CO_2 ppm	Ratio Indoor / Outdoor CO_2 Concentration
1	39	20	750	1.7
2	52	26	700	1.6
3	52	12	700	1.6
4	56	11	2440[2]	5.5[2]
5	48	23	990	2.3
6	58	19	1075	2.4
7	34	17	875	2.0

[1] Main supply and return fans to floors 4-7 shut off. Main supply and return fans to floors 1-3 running with outside air dampers closed.

[2] Sample taken in 430 ft^2 room while people were taking an examination. Comfort conditions were rather poor due to high temperature and relative humidity.

Table 4 Carbon Dioxide in Air Samples Taken From Various Floors in the Norris Cotton Federal Office Building, February 17, 1977, 1:00 to 2:30 p.m.[1, 2]

Floor	No. of People on Floor	No. of People in Room Sampled	CO_2 ppm	Ratio Indoor / Outdoor CO_2 Concentration
1	36	21	875	2.0
2	55	32	800	1.8
3	36	12	650	1.5
4	51	16	1350	3.1
5	31	22	850	1.9
6	47	16	865	2.0
7	21	12	775	1.8

[1] Main supply and return fans to floors 4-7 turned on with outside air dampers closed.

[2] Outside air concentration of CO_2 440 ppm at 5:50 p.m.

Symbols in Figures 1A and 1B

F_1 and F_3	Supply fans
F_2 and F_4	Exhaust fans
D_1 and D_4	Outside air intake dampers
D_2 and D_5	Exhaust dampers
D_3 and D_6	Return dampers

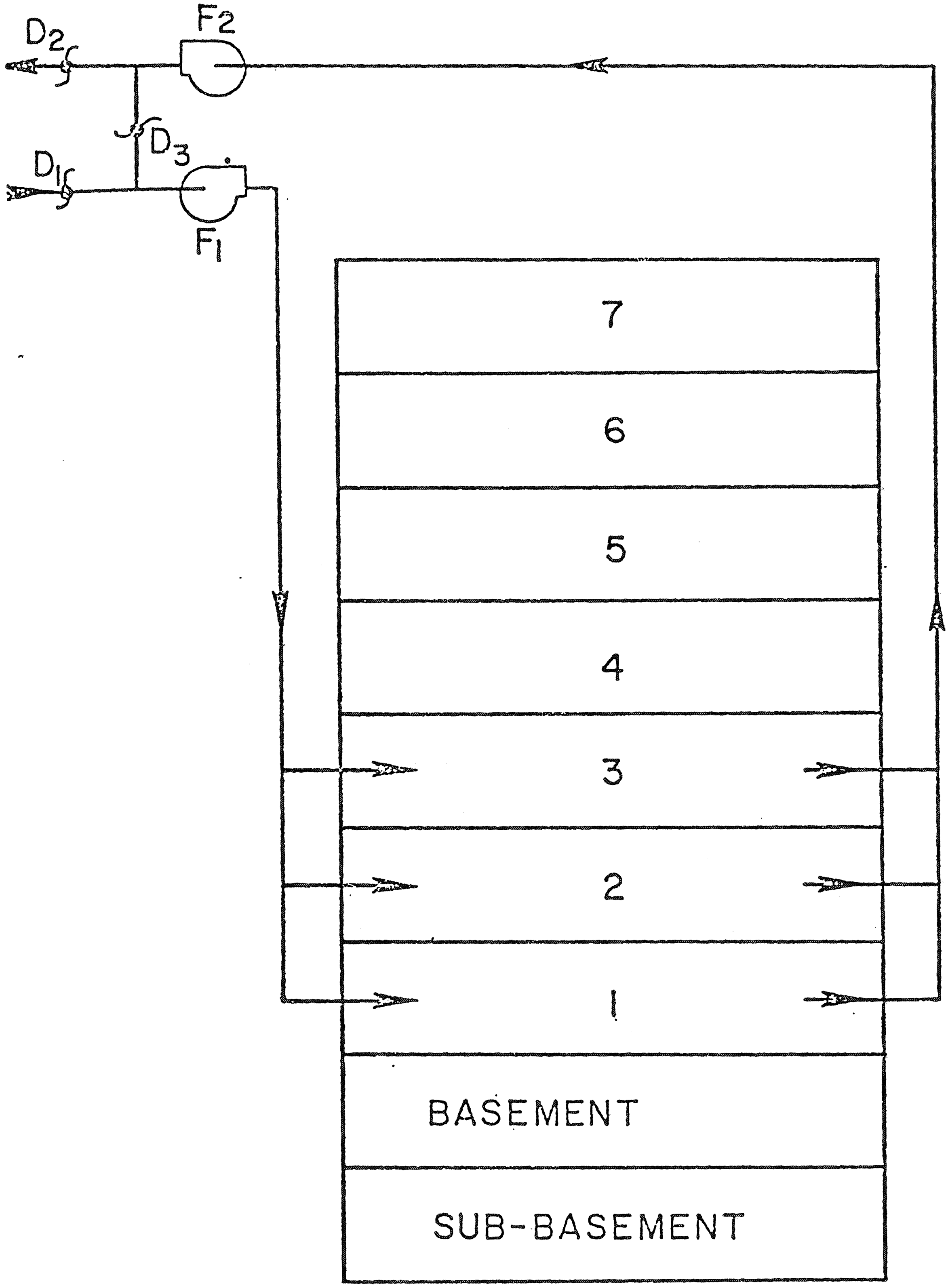

Figure 1A Simplified Schematic of Main Ventilation System of Floors 1-3

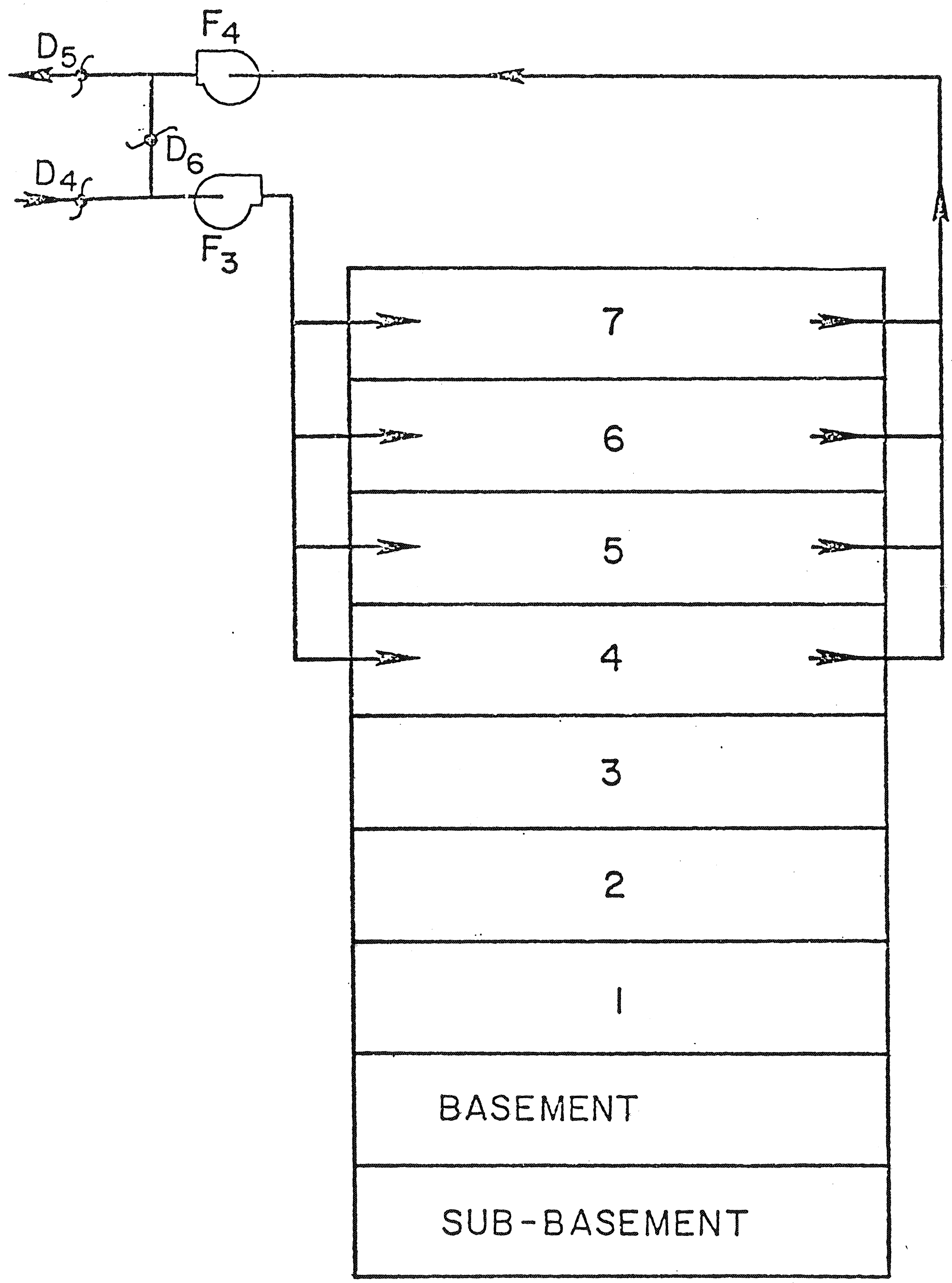

Figure 1B Simplified Schematic of Main Ventilation System of Floors 4-7

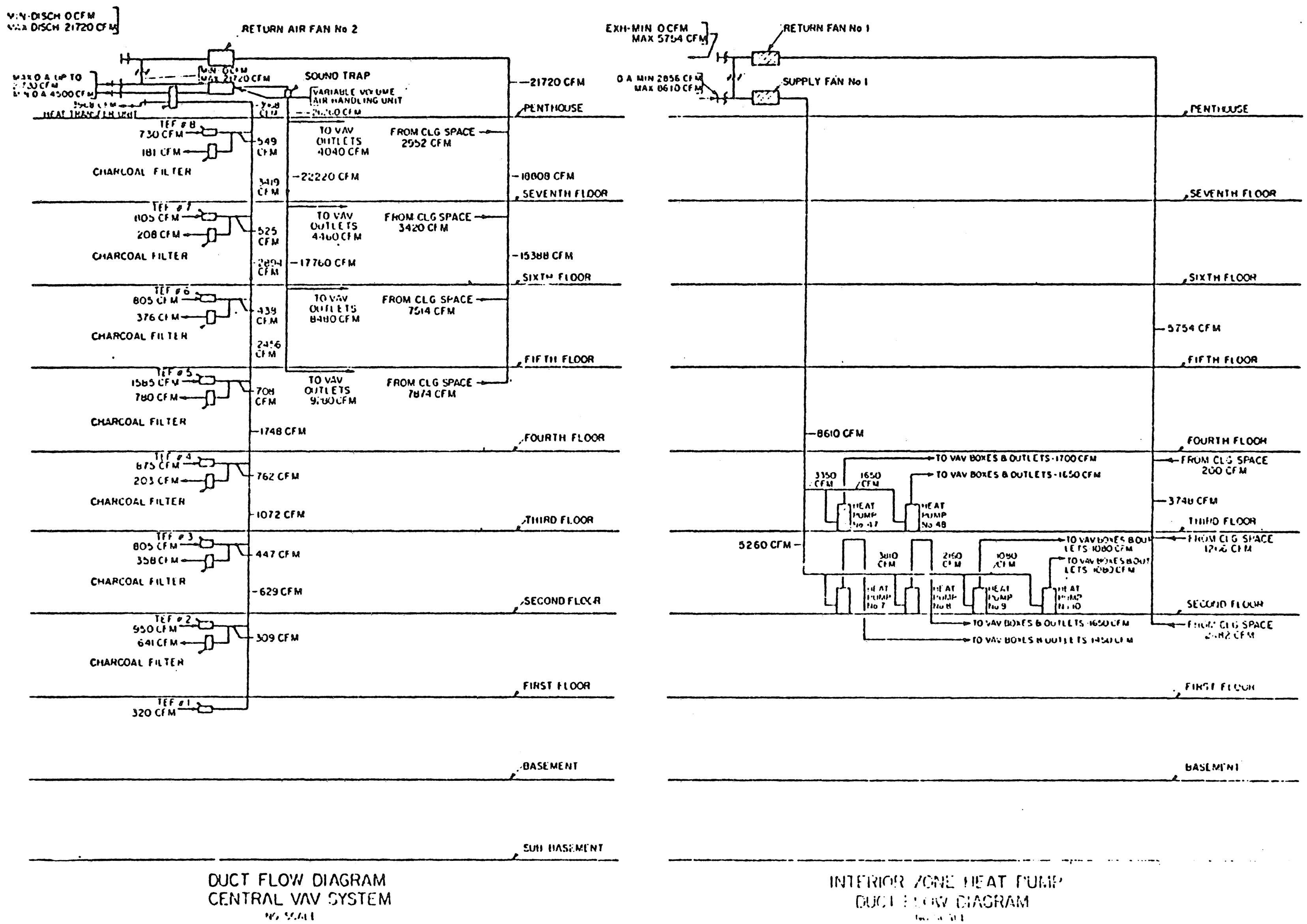

Figure 2 Diagram of Ventilation

Paper B.4.

Determination of Combined Air Exfiltration and Ventilation Rates in a Nine-Story Office Building

Wm. J. Kelnhofer*
C.M. Hunt
D.A. Didion

Introduction

In the course of retrofitting a building for energy conservation, it is usually necessary to establish the conditions prior to beginning the alterations. The extent of this determination depends upon the detail to which one wants to analyze the results. For instance, records of energy bills before and after the retrofit can be used to identify the magnitude of the energy savings but are not likely to indicate the magnitude of savings as a result of any particular conservation step. At the other extreme, complete submetering of each energy system and an establishment of the existing comfort conditions in the building are required. This latter determination is necessary so that if the energy savings are due in part to making the space less comfortable (which requires virtually no engineering innovation), this may be duly noted.

The intent of the project discussed in this paper was to establish this complete energy and comfort record for a typical multistory office building prior to the start of a retrofit program. Establishing these conditions required that measurements be made of the air infiltration that occurred in the building. Measurements had to be made in the air handling system as well as at other places inside the building. The measurements in the air handling system included the total, velocity, and static head pressure which could be used to compute air flow rates through the use of traditional techniques. In addition, the tracer gas technique was utilized simultaneously (during the same day) so that it was possible to make a comparison between the two methods. The specific tracer gas used was sulfur hexafluoride (SF_6) and the apparatus included a small gas chromatograph with an electron capture detector plus other accessories[1/] Similar apparatuses have been used to determine air leakage rates in several houses and smaller structures with considerable success[2,3,4,5/]. However they have not, to our knowledge, been used to measure air leakage rates of an occupied high rise office building.

This study cannot be cited as conclusive proof that either of the techniques are absolutely correct; however, it will be shown that there is excellent agreement between them. Considering that the two methods are based on completely different physical principles, it does give some confidence that either the direct method or the tracer gas method can be used to estimate a building's air exchange with its surroundings.

Description of Test Building

The nine story, square cross-sectional Union Plaza building, which was occupied by the Federal Power Commission in July, 1973, is located in downtown Washington, D.C. Exterior dimensions of the building are 57.6m (189 ft) x 57.6m (189 ft) x 28.3m (93 ft). The exterior walls of floors three through nine consist of precast concrete panels with exposed aggregate backed by batt insulation with 1.3 cm (1/2 in.) gypsum board on the inside. The windows are single pane of grey plate-glass, mounted in aluminum frames and sealed. Floors one and two have a mixture of store-front glass and face brick.

The first floor is below street level, but there is adequate space around the base of the building to provide entranceways on all sides including a service entrance and loading dock. The only other openings in the building are located on the roof, as shown in Figure 1. These include the elevator shaft vents, record lift shaft vent, toilet exhausts, door from west stairwell to penthouse, and first floor kitchen exhaust hood vent.

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the core and perimeter zones of floors two through nine, which have approximately 27% glass relative to the exterior facing, are serviced by the main variable air volume system. Two air handling units, each rated at 49.1 m^3/s (104,100 cfm), are located in the first-floor air handling room. One supplies air to the north riser and the other to the south riser. On each floor, the supply ducts from each of the two risers join together at the end of their runs. The air-handler room acts as a plenum.

Air which is drawn through the ceiling of each floor returns to the air handler room via the masonry duct shafts in the space not occupied by supply air risers. A maximum of 21.2 m^3/s (45,000 cfm) of outside air may be introduced into the air handler room through first-floor level air louvers connecting to the mechanical room, which has air inlet dampers to the outside. The first floor, which has a lobby, snack bar, kitchen, cafeteria, liquor store, bank and information center is supplied with air from a separate air handling unit independent of the main system.

Infiltration Rates by Tracer Gas Technique

In the measurement of air infiltration by the tracer dilution method,a tracer gas is distributed throughout a building, and the decay in concentration is measured as a function of time. The theory of the method can be briefly outlined by considering the governing equation for the uniform concentration of a tracer gas in air as a function of time:

$$\frac{dC_i}{dt} = (C_o - C_i)\frac{v}{V} \qquad (1)$$

where C_o and C_i are respectively the outside and inside concentrations of tracer at time t. v is the rate at which air enters the building. It is also the rate at which air leaves the building unless there is a buildup or loss of pressure. V is the ventilated volume of the building, and v/V is the air-infiltration rate per unit time. By proper selection of units, v/V has the units of air changes per hour.

If the outside concentration of tracer is small enough nto be neglected, equation (1) can be reduced to:

$$\frac{dC_i}{dt} = -C_i\frac{v}{V} \qquad (2)$$

Equation (2) can be integrated to give:

$$v/V = -\frac{1}{t}\ln(C_i/C_io) \qquad (3)$$

where C_{io} is the initial indoor concentration of tracer. Equuations (2) and (3) have the form of the radioactive decay law or the equation of the well mixed tank. Equation (3) can be solved directly using specific values of the variables on the right hand side; however, when manual calculation is performed it is common practice to plot $\ln\frac{C_i}{C_{io}}$ against t and calculate the infiltration rate from the slope of the line. It should also be noted that it is not necessary to know absolute tracer concentrations to calculate infiltration rates since relative concentrations, C_i/C_{io}, are all that are needed.

Concentrations of SF_6 in air were measured with a small gas chromatrograph with a pulse-mode electron capture detector. Sampling points are shown by number in Figure 2 which is an abridged diagram of the air handling units in the building and their associated space. Sulfur hexafluoride was metered into one of the fans at point A indicated in the Figure, and concentrations of the gas were monitored downstream at point 1 in the supply duct. Spot checks were also made at the other sampling points to determine tracer uniformity. In one series of tests, samples were taken from the corridors on floors two through nine as a further check on uniformity.

To determine infiltration rates, the SF_6 level was built up to a suitable level (usually about 20 ppb) allowing 15 minutes or longer to reach steady state conditions. Samples were then taken at timed intervals from point 1 and analyzed.

Figure 3 shows typical plots of relative concentration vs. time from which the total air exchange rates were calculated. These exchange rates were measured on two different days with the outside air vents closed, and with the outside air vents open, respectively. The calculated infiltration rates are indicated beside the respective plots.

Air Exchange Rates by Direct Measurement and Calculation Technique

The second, independent technique for determining the total air exchange rates involved a combination of measuring and calculating exhaust rates for the building. It was assumed that quasi-steady state conditions existed and that total air leaving the building equaled that incoming.

The building was well suited for determining exhaust rates. As described above, entrances to the building are located only on the first floor, the windows cannot be opened, and all vents associated with the main air handling system serving floors two through nine as well as the exhaust openings are located directly on the roof or in the penthouse.

There are the vents for the elevator shafts, the record lift vent, exhausts from the mens' and womens' toilets, and the door opening to the penthouse from the west stairwell. The exhaust from the first floor kitchen was not considered associated with the main air handling system. Further, direct measurement of pressure difference across exterior walls of the building indicated that floors two through nine were always slightly pressurized by the main air handling units. Thus, exfiltration could occur through the external walls and down from the second floor to the first floor. This is indicted conceptually in Figure 1.

To determine the exfiltration rates through outside air vents, air flow rates through the roof vents and exhaust units were determined from velocity measurements made with a vane anemometer. The flow rates through the walls of floors two through nine, and from the second to the first floor were calculated. The values of the two components were added to obtain the total exfiltration rates. The results are presented in Table 1 for two different conditions, outside air vents closed and open.

All of the exhaust system velocities were measured with a vane anemometer at the roof vent location. Each vent has a grill similar to that on the record lift vent located on the north side of the penthouse. The flow rate through any grill is:

$Q = A\bar{V}\eta\beta\,[m^3/s]$
A = vent area (grill off) $[m^2]$

$\bar{V}$ = average velocity across the face of the vent within the grill [m/s]

η = ratio of $\bar{V}$ with grill on to $\bar{V}$ with grill off

β = ratio of $\bar{V}$ based on long periods of operation to $\bar{V}$ based on short tests.

The procedure for the elevator vents only was to measure $\bar{V}$ for each vent with the grill off; because the grill slats made the exit flow patterns quite distorted. While the main elevators and record lift were operating, $\bar{V}$ was determined as the average of five readings taken with a vane anemometer over the face of each vent for one minute periods. The air flow through the record lift vent could be read from inside or outside the grill, i.e., inside or outside the penthouse. Thus, after finding $\bar{V}$ for the record lift without its grill by measuring from the outside, the grill was put in place and the readings repeated from inside the penthouse. The ratio of the two average readings was 0.528, which was considered the same for all vents since all grills were of the same configuration. It was found that $\bar{V}$ determined over long periods was slightly less than that for one minute periods. This was because of the unsteady flow conditions due to the somewhat random operating cycle of the elevators. Several longer tests were made and it was determined that $\bar{V}$ based on one minute test periods could be corrected satisfactorily by the factor $\beta = 0.80$. The procedure for the toilet exhausts was to measure the flow with the grill in place because it was a simple screen and the flow pattern was regular. The η value was therefore 1.

The leakage rate through the exterior walls of a building, Q in m^3/s, was calculated from:

$$Q = q\,A$$

where

q = leakage rate per unit area $m^3/(s \cdot m^2)$, depends on the wall construction (porosity) and the pressure difference, ΔP across the wall.

A = total exterior wall area m^2

In general little is known about determining q theoretically for conventional or contemporary building construction. Usually q must be determined experimentally. Fortunately, some tests were carried out in Canada on buildings similar in construction to the FPC building, and the results were reported by Shaw, et al[6] It was found that the leakage rates for the walls of these type buildings are approximately the same as those tabulated in the ASHRAE Handbook of Fundamentals—for 13-inch plain brick wall. To use this data, ΔP across the wall must be known. Therefore, measurements were made across the four walls of the FPC building using a sensitive pressure transducer. The measurements were made at the second floor level and at the ninth floor level, for the two cases, outside air vents closed and outside air vents open. The pressure inside the building was always higher than outside the building.

To determine q from the ASHRAE data, average values of ΔP from the second and ninth floor data were used. Thus,

With outside air vents closed:

$$\Delta P = 6.97 \text{ Pa } (0.028 \text{ inch } H_2O)$$

$$q = 2.8 \times 10^{-4} \, m^3/(s \cdot m^2)(3.3 \, ft^3/(h \cdot ft^2))$$

With outside air vents open:

$$\Delta P = 27.4 \text{ Pa } (0.11 \text{ inch } H_2O)$$

$$q = 7.3 \times 10^{-4} \, m^3/(s \cdot m^2)(8.6 \, ft^3/(h \cdot ft^2))$$

During the days these tests were run the wind velocity averaged <5 MPH and the temperature differences between the interior and exterior was <5°F. It would be reasonable to expect higher air exchange rates than determined here under more severe weather conditions.

The second story floor construction was such that a porosity value one-half that of the exterior wall was assumed. The roof was assumed airtight.

Final Results and Conclusions

The summary results of using both the tracer gas and direct measurement technique are listed in Table 2. The tracer gas results were directly in terms of air changes per hour; however, the direct measurement results were not and it was necessary to estimate the total unoccupied volume (net air space) of the building. This net volume determination was made by taking the difference between the total volume indicated from the architectural drawings and the volume occupied by the furniture, etc., which was approximately 15%. The occupied volume was estimated from physical measurements in a typical office. The net volume was then divided into the total air flow leaving the building to obtain the figures listed in Table 2.

Since the direct measurements employed a vane anemometer, it can be assumed that the absolute accuracy of these measurements may be in error by 10%. The tracer gas technique is estimated to have a standard deviation of .07 but a standard error of mean of only .03 air changes per hour, based on experience in other applications.

It is regarded as somewhat fortuitous that the differences between the two measurement methods was only about 3% with the fresh air vents at minimum and 6% with the fresh air vents at maximum considering the typical error of many of the measurement techniques used the necessity for estimating some components of the air exchange. However, there were a number of factors in this particular experiment which tended to reduce the errors in determining total air exchange.

The fundamental criteria for the tracer gas technique to be accurate is good mixing and good sampling. This building was ventilated by two fans within supply and return ducts which were interconnected on every floor. This in effect, made the entire building a single zone ventilation system. This effect was verified by noting that upon injection of the tracer in the supply fan at point A of Figure 2, detection of almost equal amounts was indicated at positions 4 and 3 at the same time. Also once the gas supply was shut off, the decay rates at any of the measurement stations were the same. A second factor which made this test environment ideal was the weather. With low wind speeds, small interior/exterior temperature differences, and a continuously positive pressurized building, the variations due to stack effect, etc., within the building were minimal. It was thus possible to obtain good sampling from the equipment room alone with only spot checks on the second and ninth floors to assure uniformity. Applications where building and weather conditions deviate from those found here may require considerably more effort and/or may result in considerably less accuracy.

Two observations concerning this specific building were that (1) the overall air system was not balanced (positive pressure condition) and (2) a significant portion of conditioned air was being pumped out the elevator vents. This latter condition indicates that there would be good potential for energy conservation through either using thermal recovery from the exhaust or by recycling of the air itself.

References

1. Hunt, C.M. and Treado, S.J., "A Prototype Semi-Automated System for Measuring Air Infiltration in Buildings Using Sulfur Hexofluoride as a Tracer", National Bureau of Standards Technical Note No. 898, March 1976.
2. Bahnfleth, D.R., Moseley, T.T., and W.S. Harris, "Measurement of Infiltration in Two Residences, Part I: Technique and Measured Infiltration, Part II: Comparison of Variables Affecting Infiltration", ASHRAE Transactions, Vol. 63, pp. 453-476, 1957.
3. Jordan, R.C., Erickson, G.A., and R.R. Leonard, "Infiltration Measurements in Two Research Houses", ASHRAE Journal, May, 1963.
4. Coblentz, C.W., and P.R. Achenbach, "Field Measurements of Air Infiltration in Ten Electrically-Heated Houses", ASHRAE Journal, July, 1963.
5. Hunt, C.M., and D.M. Burch, "Air Infiltration Measurements in a Four-Bedroom Townhouse Using Sulfur Hexaflouride as a Tracer Gas", ASHRAE Transactions, Vol. 81, Part I, 1975.
6. Shaw, C.Y., Sander, D.M., and Tamura, G.T., "Air Leakage Measurements of the Exterior Walls for Tall Buildings", ASHRAE Transactions, Vol. 79, Part II, pp. 40-48, 1973.

7. "Infiltration and Natural Ventilation", ASHRAE Handbook of Fundamentals, Chapter 19, 1972.

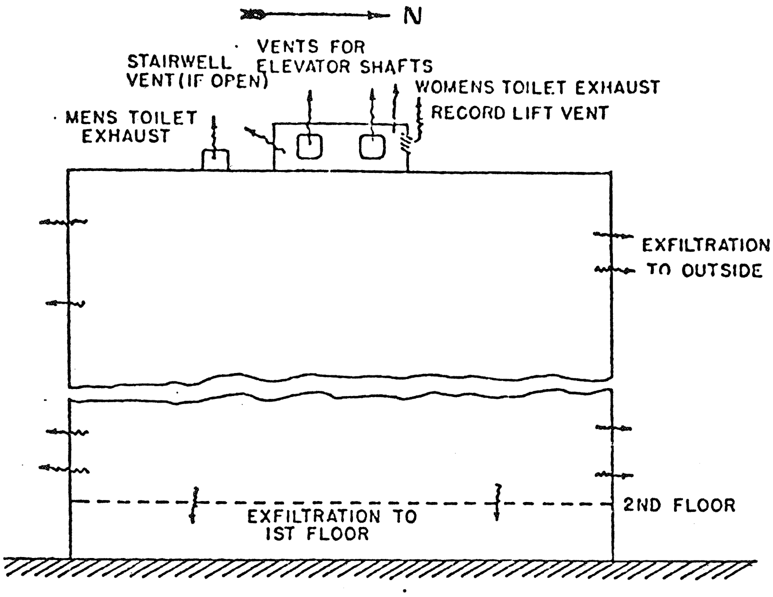

FIGURE 1

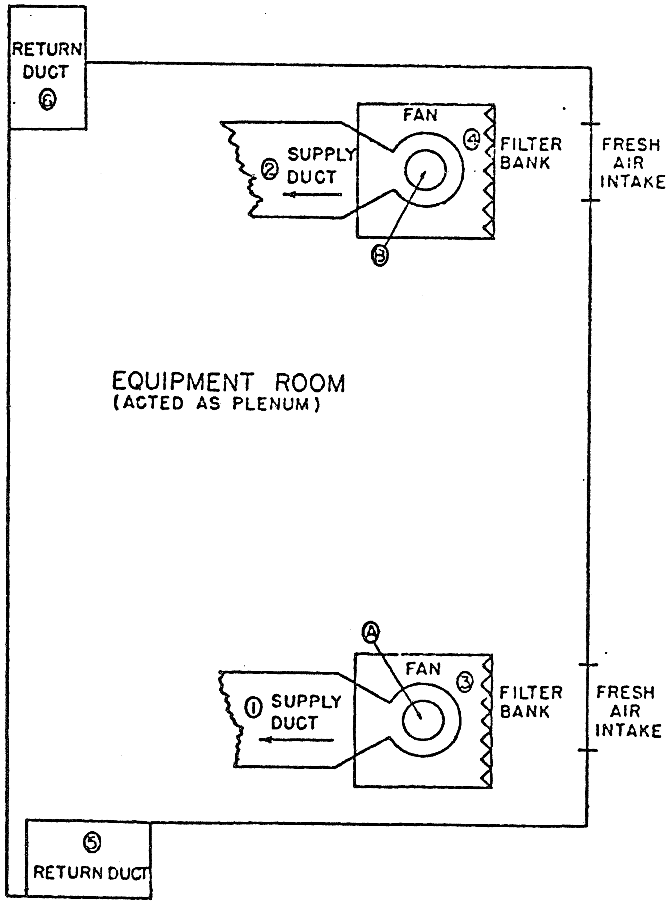

FIGURE 2

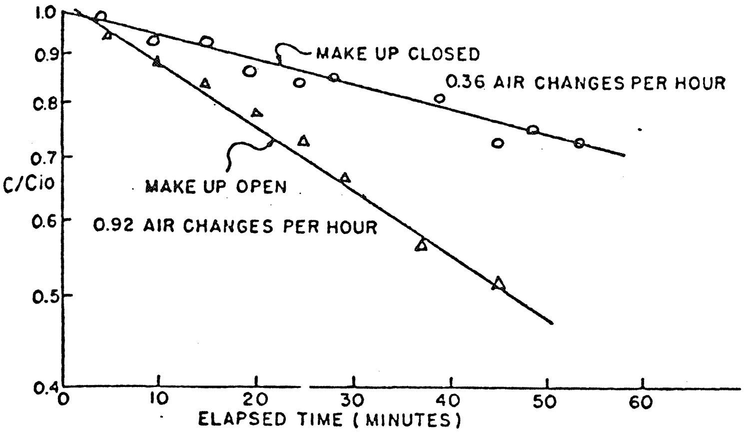

FIGURE 3

Table 1

RESULTS OF DIRECT METHOD DETERMINATION OF AIR EXCHANGE

	Air Flow Rate					
	Outside Air Vents Closed			Outside Air Vents Open		
	m^3/s	cfm	% Total	m^3/s	cfm	% Total
4 Elevator Vents	1.5	3100	22	4.7	10000	29
Toilet Exhausts	3.1	6500	46+	3.8	8000	24
Stairwell to Penthouse	0	0		2.5	5200	14+
1st/2nd Floor Exch.	0.47	1000	7	1.2	2600	7+
Exterior Wall Leakage*	1.7	3500	24+	4.2	9000	25+
	6.7	14100	99+	16.4	34800	99+

*Pressure Difference Between Interior and Exterior: 6.97 Pa (.028"H_2O) — 27.4 Pa(.11"H_2O)

+Implies a fraction of 1% greater than.

Table 2

RESULTS OF AIR EXCHANGE MEASUREMENTS

AIR EXCHANGE RATES, hr^{-1}

	TRADITIONAL METHOD	TRACER GAS METHOD
OUTSIDE AIR VENTS CLOSED	.35	.36
OUTSIDE AIR VENTS OPEN	.87	.92

DISCUSSION

Paper B.4. Kelnhofer, Hunt and Didion, "Determination of Combined Air Exfiltration and Ventilation Rates in a Nine-Story Office Building"

Ralph Torborg

Please comment on other tracer gases (such as methane). How do they (methane) compare to SF_6?

David Didion - Response

The only simultaneous comparison we have made of different tracer gases was between SF_6 with molecular weight of 136 and He with a molecular weight of 4 (C. M. Hunt and D. M. Burch, ASHRAE Transactions 81, Part I, 186-201, 1975). This comparison was performed in a 4-bedroom townhouse. The He results averaged slightly lower than those obtained with SF_6. The purpose of the comparison was to determine if He disappeared faster than SF_6 because of its faster diffusion rate. This effect was not observed.

Other gases have been used as tracers such as: ethane (R. H. Elkins and C. W. Wensman, paper presented at Institute of Gas Technology Conference on Natural Gas Research and Technology, Chicago, Illinois, March 3, 1971); nitrous oxide (O. M. Lidwell, J. Hygiene 58, pp. 297-305, 1960); carbon dioxide (J. E. Hill and T. Kusuda, ASHRAE Transactions 81, Part I, pp. 168-185, 1975); and carbon monoxide (R. Prado, R. G. Leonard, and V. W. Goldschmidt, Purdue University Report). There are also additional gases which might be used as tracers, but we are unaware of any simultaneous comparison of different gases other than the one cited.

Charles Erlandson

Was the positive pressure of .028" constant on all floors? Did you take readings at higher wind velocities?

David Didion - Response

Pressure differences across the outer walls were measured on the second and ninth floors only, and for practical purposes they did not vary from each other. Readings at higher wind velocities were not taken.

Preston McNall

Could the OA be measured directly? If so, OA-exhaust air equals infiltration (or exfiltration) and could be a check on the calculated exfiltration.

David Didion - Response

A pitot-static tube traverse in the outside air ducts could have been used to determine outside air rate with the outside air vents open. This was not done because of time limitations. However, your suggestion is well taken and appreciated.

In response to this question the authors' curiosity was sufficiently aroused to cause them to return to the building to obtain an outside air quantity measurement. Considering that it was almost two years since the other measurements and that institutional constraints disallowed a proper pitot traverse, the measurement could only be very approximate. The only convenient place to use a vaned anemometer was at the exit planes of the outside air ducts as they entered the fan room. Unfortunately the dampers are also at this plane and the airflow correction factors for such dampers is unknown. However, assuming a correction factor of .8 the total air flow was determined to be about 37000 cfm for the dampers in the fully open position.

John Palmer

Was any attempt made to evaluate change in elevator shaft openings in relation to outside air vents being opened and closed?

David Didion - Response

The elevator shaft vents for the building are of fixed geometry and always open. If the exfiltration from these vents could be reduced or eliminated, a substantial savings would result.