Development and Field Verification of a Model of Excess Infiltration and House Air Infiltration for Single-Family Residences
Final Report for 1979

Institute of Gas Technology
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# DEVELOPMENT AND FIELD VERIFICATION OF A MODEL OF EXCESS INFILTRATION AND HOUSE AIR INFILTRATION FOR SINGLE-FAMILY RESIDENCES

## FINAL REPORT FOR 1979


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This report presents the results of 3 major tasks dealt with during calendar year 1979, namely the completion of the development of a generalized model of air infiltration, partial refinement of the model by the development (and inclusion into the model) of 3 support models (for total crackage, wind shielding and structural permeability), and partial verification of the model by comparison to detailed, measured house infiltration data obtained by other investigators in 2 test homes. The report also presents a review of literature air infiltration models and of their limitations.

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RESEARCH SUMMARY

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| Title | Development and Field Verification of a Model of Excess Infiltration and House Air Infiltration for Single-Family Residences<br>GRI Code: GRI 79/0031<br>GRI contract number: 5011-341-0111 |
| Contractor | Institute of Gas Technology |
| Principal Investigators | Robert A. Macriss, Thomas S. Zawacki, James T. Cole |
| Time Span | 12 months |
| Major Achievements | An air infiltration model and program has been developed, based on fundamental principles, and actual data obtained in 3 heavily instrumented homes. The model has been partially refined to allow the input of easily measured parameters such as weather data (temperature, wind speed and direction), an estimate of the effect of shielding of the surrounding structures on the actual wind force, the total measurable crack length, and a single permeability coefficient equivalent to an average crack width. The model has been partially verified by simulating successfully the infiltration characteristics of two test homes of other investigators. |
| Recommendations | For the first time, a practical, generalized, but cost effective, model of air infiltration for existing homes (heated by central fossil-fueled furnaces and boilers) has been developed and tested on a very limited number of homes. In order to ensure that the model can be used to estimate the infiltration characteristics of the majority of different style, construction, size and age existing homes we recommend the following:<br>• The model refinement effort be continued and completed by the inclusion of the effect of vent-fan usage and door and window openings on hourly and daily air infiltration rates<br>• The model verification effort be continued and completed by comparison to data from as many other homes and installations as possible<br>• The model be used to prepare a fully dynamic (hour-by-hour) infiltration load-routine that could be used with existing public and private building Energy Estimation Programs such as E-Cube, NBS-LD, DOE-2, etc. |

**Description of Work Completed**

In the past several years, gas-industry-supported research has made significant progress toward the understanding and improvement of the performance of conventional central gas furnace installations. It is important, however, that the ability to accurately predict the real performance of central gas furnaces be developed in order to assess the values of new conservation measures and ideas and concepts that are now being researched. The missing link that will tie all recent advances in this area together is a model of excess infiltration occasioned by the existence of a chimney in a residence (and by furnace operation) and a more general house infiltration model, the development of which is the subject of this program.

During calendar year 1979, this phase of the program dealt with 3 major tasks, namely, the completion of the development of a generalized model of air infiltration, partial refinement of the model by the development (and inclusion into the model) of three (3) support models (for total crackage, wind-shielding and structural permeability), and partial verification of the model by comparison to detailed, measured, house infiltration data, obtained by other investigators in two (2) test homes.

Among the accomplishments that have resulted from the 1979 phase of the program, the following are considered worthy of note:

- An air infiltration model and program have been developed, based on fundamental principles and actual data obtained in three (3) well instrumented test homes (under "intensive" testing). This is the first such comprehensive, generalized model for use in homes equipped with fossil-fueled central furnaces and boilers, not requiring testing at the site for its use.

- The IGT model has been partially refined to account for the real effects not only of weather and furnace operation but also of:
  - Total (measureable and hidden) crackage in actual homes
  - The actual permeability coefficient of the structures building components (in essence a measure of the crack width)
  - The effect of shielding of wind forces by objects (other buildings, trees, etc.) in near proximity to the house.

Therefore, the model is especially suited for use with the storehouse of existing homes. Use of the model in these homes can be made to more properly select and re-size central space conditioning equipment, and to ascertain the energy and cost effectiveness of retrofit approaches to reduce excessive air infiltratio and of means to control contaminants in the indoor environment.

- The IGT model has been partially verified. To accomplish verification the model and program have been used to simu ate successfully the infiltration characteristics of two test homes of other investigators (Research Council of Canada Test Home No. 1, Princeton University Test Home No. 2). The first test-home is a single-story home with basement, of wood-frame construction, equipped with an oil-fired central space heating furnace. The other is a 2-story interior unit (of a multi-unit low rise structure) with basement, of wood-frame construction, equipped with a gas-fired central space heating furnace.

- The IGT model and computer program was preliminarily recast as the first step to producing an hour-by-hour (dynamic) subroutine to general building energy simulation programs such as AGA's E-Cube, NBS-LD, DOE-2, and similar programs, which would enable these programs to estimate the contribution of infiltration to the total building load and, therefore, energy requirements.

- The IGT model and preliminary results of its refinement and partial verification were presented at the 72nd Annual Air Pollution Control Association (ACPA) Annual Meeting held in Cincinnati, Ohio on June 24-29, 1979.

## GRI COMMENTS

Air infiltration - exfiltration - is a major contributor to the heating load imposed on single family dwellings. In addition to being the least known heat loss mechanism, it is the most difficult to predict. Consequently, air infiltration has been the subject of a considerable amount of recent study.

The Institute of Gas Technology (IGT) has built on existing air infiltration studies and provided much of their own data for the development of the IGT infiltration model. The model uses weather data, house characteristics and furnace operation data to predict the amount of air infiltration. The IGT model has been proven accurate when used to predict the air infiltration in highly instrumented test houses of IGT and other researchers.

It is the intent of GRI to further refine the model, further determine the accuracy of the model and adapt the model so that it can be used in dynamic heating and cooling load routines for major computer programs.

# EXECUTIVE SUMMARY

In the past several years, gas-industry-supported research has made significant progress toward the understanding and improvement of the performance of conventional central gas furnace installations. It is important, however, that the ability to accurately predict the real performance of central gas furnaces be developed in order to assess the values of new conservation measures and ideas and concepts that are now being researched. The missing link that will tie all recent advances in this area together is a model of excess infiltration occasioned by the existence of a chimney in a residence (and by furnace operation) and a more general house infiltration model, the development of which is the subject of this program.

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Among the accomplishments that have resulted from the 1979 phase of the program, the following are considering worthy of note:

- An air infiltration model and program have been developed, based on fundamental principles and actual data obtained in three (3) well instrumented test homes (under "intensive" testing). This is the first such comprehensive, generalized model for use in homes equipped with fossil-fueled central furnaces and boilers, not requiring testing at the site for its use.

- The IGT model has been partially refined to account for the real effects not only of weather and furnace operation but also of:

  - Total (measurable and hidden) crackage in actual homes

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  - The effect of shielding of wind forces by objects (other buildings, trees, etc) in near proximity to the house.

Therefore, the model is especially suited for use with the storehouse of existing homes. Use of the model in these homes can be made to more properly select and re-size central space conditioning equipment, and to ascertain the energy and cost effectiveness of retrofit approaches to reduce excessive air infiltration and of means to control contaminants in the indoor environment.

- The IGT model has been partially verified. To accomplish verification the model and program have been used to simulate successfully the infiltration characteristics of two test homes of other investigators (Research Council of Canada Test Home No. 1, Princeton University Test Home No. 2). The first test-home is a single-story home with basement, of wood-frame construction, equipped with an oil-fired central space heating furnace. The other is a 2-story interior unit (of a multi-unit low rise structure) with basement, of wood-frame construction, equipped with a gas-fired central space heating furnace.

- The IGT model and program are presently being used to prepare an air infiltration load subroutine (and user manual) for use with general building energy simulation models such as AGA's E-Cube, DOE-2, and similar programs.

- The IGT model and preliminary results of its refinement and partial verification were presented at the 72nd Air Pollution Control Association (APCA) Annual Meeting held in Cincinnati, Ohio on June 24-29, 1979.

Any future work on this program should mainly concentrate on the completion of the model's refinement, by the inclusion of the effect of vent-fan usage and door and window openings on hourly and daily air infiltration rate variation; also, on additional model verification activities, in order to strengthen the general applicability to typical structures and installations. In addition, the use of the model to prepare a dynamic infiltration-load subroutine should be part of the program.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

# INTRODUCTION

In 1974, a comprehensive series of studies was begun at the Institute of Gas Technology (IGT), funded by the American Gas Association (A.G.A.), to quantify the factors affecting seasonal efficiency of space heating furnaces. As part of A.G.A. Project HA-4-31, IGT developed initial data (in a laboratory model of a house) on how furnace cycling, wind speed, and structure looseness (or air change rate) affect chimney flow by simulating a specific installation, the Canton Gas Test Home, and houses similarly equipped.

During 1976, as part of A.G.A. Project HC-4-33, the study was extended to cover homes "looser" than the Canton home, installations with smaller and larger furnace inputs, and vent pipe and chimney diameters. As a result of this study, a comprehensive, generalized, semi-empirical model was developed for chimney flow and energy losses associated with the operation of a central gas furnace and chimney-vent system in a residence.

During 1977, IGT conducted a field study in 20 test homes to verify the IGT flue-loss model, to extend its applicability to a wider spectrum of installations and residences, and to obtain additional practical data from the structures (e.g., crack lengths) in order to simplify the model for use by utilities, contractors, and furnace manufacturers. The results of this program extended the applicability of the model to installations equipped with furnace retrofits (e.g., derates and vent restrictors) and provided a data base useful to parallel A.G.A. and gas industry programs such as SHEIP, E-Cube, and Honeywell's H-Flame model.

The results also indicated that the excess house infiltration, due to the existence and operation of a furnace, is variable, and depends on the structure, installation, and climate. They also pointed out the need for a comprehensive model of air infiltration describing these interactions, a tool that would ultimately be used to accurately predict the real performance of central gas furnaces and through which new conservation measures, ideas, and concepts could be properly assessed.

During 1978, IGT conducted a field study to acquire data for the development of a model for house air infiltration. The major task of this study involved "intensive" testing in three homes to provide needed inputs for modeling purposes (one ranch and two 2-story homes) and continuation of the "extensive" testing (begun in 1977) in over 20 field test homes in the Chicago metropolitan area. A large amount of infiltration and other data were obtained in these homes and were used as a basis for the preliminary formulation of a new air infiltration model.

This report covers the 1979 phase of the program which encompassed the continuation and completion of the development of the infiltration model, partial refinement of the model by the inclusion of three support models (for total crackage, wind-shielding and structural permeability), and the partial verification of the model by comparison to house infiltration data obtained by other investigators. In addition, this report covers the preparation of a computer program for the general use of the model and the preliminary interface for the transformation of the model to produce an infiltration-load program for use with residential building energy calculation and load programs such as E-Cube, DOE-2, etc.

# AIR INFILTRATION MODEL DEVELOPMENT

Air infiltration in existing (and new) homes is becoming increasingly important and the development of a practical and cost effective means to estimate it through a generalized approach or modeling, not now available, is desirable. This is particularly true for residential structures equipped with fossil-fueled furnaces and boilers and, among these, the storehouse of existing homes is the more challenging. Use of such a generalized model can be made to more properly select and re-size central space conditioning equipment to attain high energy utilization efficiencies (as the infiltration equipment is becoming a more important factor of the total heating/cooling load) because of retrofit insulation, thermostat setback, etc.

Such a practical model (not requiring testing at the site) can also be used to ascertain the energy and cost effectiveness of retrofit approaches to reduce excessive air infiltration, and of means to control the level of contaminants in the indoor environment.

## 1.0 Existing Models

In contrast to the dynamic models available for heat transfer by radiation, conduction, and convection through the building envelope, the state-of-the-art for predicting heat transfer by infiltration is relatively primitive, particularly for residential structures. This is surprising in view of the fact that infiltration accounts for a major fraction (25% to 50%) of the total heating and cooling loads in residential buildings. Furthermore, the infiltration-exfiltration characteristics of a house interact with the venting system of the fossil fuel heating system, thus adding to the heat load and decreasing the seasonal utilization efficiency of the furnace.

### 1.1. Current ASHRAE Methods

ASHRAE describes two methods[1] for estimating infiltration in residential buildings. The first, and most commonly used, is the air change method, which is based on assuming an air change rate for each room and averaging over the whole house volume. The ratios assumed for each room are dependent on the number of walls with exterior windows and doors and the type of usage each room experiences. Typical air change rates for various types of rooms provided by ASHRAE are presumably based on past experience.

In a somewhat more sophisticated method, known as the crack method, the estimates are based on measured leakage characteristics of the building components (windows, doors, and walls) at selected pressure differentials from 0.1 to 0.5 inch $H_2O$. It is necessary, therefore, to assume an appropriate pressure differential to which the building components will be exposed.

The leakage characteristics of many of the building components, such as windows and doors, are reasonably well documented, although large variations can occur, depending on design, quality control in manufacture, and, particularly, on the quality of installation. However, the leakage characteristics of many other building components such as sill plates, ceilings, and electrical wall outlets have not been well characterized. Although it is commonly assumed that crackage around windows, doors, and sill plates are the primary sites of infiltration, two recent studies indicate that more than 50% of the permeability of actual homes may be at other sites, including wall outlets, ceiling, exhaust vent, and chimneys.[2,3]

The major limitation of the crack method is the fact that no adequate model exists for estimating the pressure differential to which the various components are actually exposed, particularly in residential structures. The pressure differentials, $\Delta P$, in the range assumed in the ASHRAE data (0.1 to 0.5 inch $H_2O$), appear to be much too high. Only windward walls could experience pressure differentials in this range, with non-windward walls likely to experience pressure differentials less than 0.02 inch $H_2O$.

1.2. Achenbach-Coblentz Correlation

Another approach to the prediction of infiltration rates is based on the empirical Achenbach-Coblentz correlation[4] derived by regression analysis of data from two test homes at the University of Illinois[5] and tested against 10 electrically heated homes in Indiana.[4] The correlation takes the form —

$$I = A + B \times WS + C \times \Delta T \qquad (1)$$

where —

| | | |
|---|---|---|
| $I$ | = | infiltration rate |
| $WS$ | = | wind speed |
| $\Delta T$ | = | indoor-outdoor temperature difference |
| A, B, and C | = | empirical constants characteristic of the particular structure. |

The constant A presumably represents the contribution of vent fan operation and door openings at zero wind speed and $\Delta T$. The constants B and C are determined by the permeability and other characteristics of the structure, and will vary from house to house. For example, the original Achenbach-Coblentz formula for electric homes was —

$$I = 0.15 + 0.013\ WS + 0.005\ \Delta T \qquad (2)$$

The NBS-LD dynamic simulation model for estimating energy consumption in residential buildings, although otherwise sophisticated, uses the Achenbach-Coblentz formula with the constants arbitrarily increased by two-thirds to "more closely correspond to a typical house" (presumably a fossil fuel heated house).[6] The constants found in other studies, however, have varied widely as follows:[5,7,8,9]

A = 0.10-0.8
B = 0.013-0.084
C = 0.005-0.016

Laschober and Healy[8]. in a later study, found that the wind coefficient B for one house varied from 0.02, with winds normal to the narrowside of the house, to 0.084 on the broadside. They also found that the presence and operation of a gas furnace contributed significantly to the overall infiltration (equivalent to increasing the constant A by 0.083). Thus, the coefficients must be determined empirically for each house, and, as yet, no one has successfully modeled these constants in terms of measurable house structural characteristics. However, there are more important limitations to the method.

The Achenbach-Coblentz approach assumes that the infiltration rates are directly proportional to $\Delta T$ and to WS and that these components are additive; these assumptions are not theoretically tenable. First, the relative dependence of infiltration on $\Delta T$ and wind speed changes gradually and continuously, from complete dependence on $\Delta T$ at zero wind speed to complete dependence on WS at wind pressures sufficient to induce a positive pressure in the house (about 20 mph at $\Delta T$ = 75 for a 2-story house), depending on height and shape of the house. The equation, therefore, cannot give even reasonable approximations over the whole range of ambient conditions of interest. Second, the model is not set up to reflect the interactions between such parameters as furnace operation (or vent fan operation) and the whole house infiltration so that their effect can be evaluated.

### 1.3. The Princeton Studies

The linear regression equation discussed above may be expanded to include other parameters, such as furnace operation and door openings, to improve the quality of correlation, but the results still tend to be highly erratic, as shown recently by Malik[10] in the Princeton studies. This is primarily because the analysis does not take into account the complex interactions between wind speed and indoor-outdoor temperature differences, as well as furnace and exhaust fan operation. This view has been recently corroborated by Sinden[11] (Princeton University) on the basis of a simple analysis of the interactions between wind and house buoyancy forces on the windward and leeward walls of a structure. The analysis shows that wind and temperatures can be simply additive or in certain cases can be subtractive. Most of the time they are complex. Sinden concludes that "the complexity of wind-temperature interaction...is bad news for computer modelers, since it appears unlikely that there exists any simple formula that universally represents natural ventilation in buildings."

Also recently, Harrje[12] has suggested the addition of a cross-product terms (WS) ($\Delta$T), to reflect the interactions between the two parameters, i.e.

$$I = A + B(WS) + C(\Delta T) + D(WS)\ (\Delta T) \qquad (3)$$

Such a model has recently been evaluated by Malik[10] for infiltration in two townhouses with mixed success. The model was adequate for high wind speeds, having a large component normal to the exposed faces of the townhouses. However, the model appeared to be inadequate for winds at low speeds, regardless of direction, or for high wind speeds having a small normal component to the exposed face. He attributes these differences to the complex interactions between wind and house buoyancy forces. Therefore, this model also does not reflect the effect of interactions over the whole range of ambient conditions. Furthermore, the constants A, B, and C still depend on the structural characteristics of the house and wind direction and must be determined empirically.

## 1.4. The Hittman Approach

The proprietary, Correlated Residential Energy Analysis Program developed by Hittman Associates[6] utilizes the Achenbach-Coblentz infiltration model (as does the NBS-LD program) to predict infiltration loads, but the empirical constants for the latter model were evaluated by a mass flow balance analysis of the original Achenbach-Coblentz data on crackages, wind speed, and direction, and the resulting infiltration rates. Basically, their program used a mass balance equation to estimate the indoor pressure resulting from wind pressures imposed from various directions. The effects of fan and furnace operation were simulated as constant flows. These pressures were then used to estimate the flow rates across each component as well as the overall infiltration rate. The individual component characteristics then could be used to estimate the required Achenbach-Coblentz constants for any house whose structural characteristics are known.

Hittman Associates[13] have recently revised the linear regression equation to a somewhat more acceptable form, as follows:

$$I = OC\ [A + B(\Delta T) + C(WS)^2]^{0.66} \qquad (4)$$

where —

OC = (orifice coefficient) - $\frac{\Sigma OA}{V}$

ΣOA = summation of orifice areas over the whole structure

V = structure volume.

The quantities (ΔT), WS, A, B, and C are as defined in Equation 1.

Orifice areas are estimated by multiplying the appropriate crack lengths by the estimated crack width. Thus, the equation takes the general form of the equivalent orifice method (cracks method):

$$I = k(\Sigma OA)\ (\Delta P)^n \qquad (5)$$

where k is an equivalent orifice constant. In this form, the measurable permeability characteristics of different structures can be used instead of empirical constants. The constants A, B, and C, used to define the relative contributions of wind speed and indoor-outdoor $\Delta T$ to the driving force, $\Delta P$, are also determined by structural factors as well as wind direction and must be determined empirically for each house and for each different wind direction. Furthermore, because of the interactions between the different driving forces, the so-called constants B and C undoubtedly vary as the ratio of $WS/(\Delta T)^{1/2}$. Since the model does not take into account these interactive effects, the model cannot be accurate over the whole range of ambient conditions.

### 1.5. The NRC (Canada) Method

The mass balance approach has already been used successfully by the National Research Council of Canada in developing a FORTRAN IV infiltration model[14,15] for multi-story commercial buildings, including the effect of stack action and exhaust or pressurization fan action, as well as wind pressures. Infiltration is calculated by writing the mass balance equations for each floor and shaft and solving the resulting nonlinear simultaneous equations. The input parameters include —

- Building leakage characteristics
- Net air supply by air handling system
- Wind pressure coefficients for 16 directions
- Indoor and outdoor temperatures.

Infiltration rates are calculated for each specified combination of outdoor temperature, wind speed, and direction and are used as a subroutine for the heating and cooling load calculation program.

## 2.0 The IGT Basic Model

### 2.1. Conceptual Approach

The discussion in the previous section makes clear the need for a dynamic infiltration model which can be used, in a practical way, to improve our ability to perform equipment sizing for heating and cooling, to carry out energy analysis of residential buildings, and to understand and control the level of contaminants in the indoor environment. More so, such a model must be based on fundamentals, and must include the interactive effect of multiple forces that affect infiltration (from within and without the building envelope), including people's style of living.

The modeling approach we adopted for this purpose is based on the simultaneous solution of mass balance equations for infiltration and exfiltration, and chimney flow equations (for homes equipped with fossil fueled furnaces), with the basic relationships developed from data obtained in a laboratory model of a one-room home.[16] These relationships were further embellished by results obtained in three "intensive" test homes which provided the likely effects of infiltration of shielding of the structure by adjacent structures or topography, non-uniform structural permeability, and height discontinuity (for 2 and 3-story structures).[17]

For its use to be practical, the model requires only data readily available for the structure, the heating system, and weather data, and does not require testing. In order to include the aggregate (over a season) effect of the occupants' style of living on infiltration, the components of the preliminary model were tested against data obtained (for a period of 2 years) in 23 actual homes in the Metropolitan Chicago area[18] and other data from the literature.[19]

### 2.2. Basic Formulations

The basic driving forces for infiltration are the pressure differentials across the various components of the building envelope generated by the following:

- Wind pressure
- House buoyancy forces due to indoor-outdoor temperature differential, $\Delta T$
- Fan exhaust or pressurization
- Chimney buoyancy forces generated by $\Delta T$ and by furnace operation.

These pressure differentials, $\Delta P$, act upon the various orifices and cracks in the building envelope to produce flow according to classical orifice theory —

$$F = \frac{1}{R} \Delta P^n = K \Delta P^n \qquad (6)$$

where —

$F$ = flow rate, CF/min

$R$ = resistance to flow, in. $H_2O$/CF-min

$K$ = flow coefficient, = $\frac{1}{R}$ = CF/min-in. $H_2O$

$\Delta P$ = differential pressure across the orifice, in. $H_2O$

$n$ = power function between 0.5 and 1.0.

The value of the power, n, depends on the relative contribution of kinetic and viscous forces to the energy loss incurred in flow. If the losses are primarily kinetic, n will be close to 0.5 rather than 1.0 which is approached in viscous flow. The literature indicates that flow in the types of orifices found in residential structures will be of the order of 0.5 to 0.65.[1]

In reality, the driving force, $\Delta P$, acting on a particular orifice varies widely depending on its location with respect to wind direction and height of the house. The actual pressure drop, $\Delta P$, across a particular orifice is determined by the difference between the dynamic pressure on the outside of the orifice imposed by wind forces, $\Delta P_w$ (for which a reasonable model exists), and the resultant indoor-outdoor static pressure difference, $\Delta P_r$:

$$\Delta P = \Delta P_w - \Delta P_r \tag{7}$$

where $\Delta P_r$ is the sum of two indoor-outdoor static pressure difference effects.

One of these pressure differences is $\Delta P_B$, the static pressure difference at a particular height in the house, resulting from the vertical gradient induced by the indoor-outdoor temperature difference only. Its value may be estimated from the indoor-outdoor temperature difference, $\Delta T$, and the height of the orifice above or below the structure's <u>neutral zone</u>. The other is $\Delta P_x$, the static pressure difference induced by the combined effects of wind, chimney buoyancy, and fan forces (at mass balance). The pressure difference, $\Delta P_x$, affects the whole house equally, depending on communication between rooms and between floors.

We can, therefore, define the flow, F, through a particular orifice in terms of the following equation:

$$F = OC\ [\Delta P_{W} - (\Delta P_{B} + \Delta P_{X})]^{n} \qquad (8)$$

where OC is the measurable orifice coefficient for the particular orifice. All of the parameters in Equation 8 are calculable or measurable except the flow, F, through the orifice, and $\Delta P_X$. The latter is determined by mass balance between the exfiltration and infiltration through all of the orifices in the house. In order to compute the whole house static pressure difference, $\Delta P_X$, as well as the overall infiltration rate, all of the orifices in the house are characterized in terms of Equation 8 and by setting up an overall mass balance equation for infiltration-exfiltration through all orifices. Such an equation is then solved by the method of successive approximations.

The basic model assumes (for simplicity) that the vertical gradient in permeability is uniform but variable from wall to wall. With regard to the usual levels of wind velocities and indoor-outdoor temperature differences characteristic of the four seasons, at least four distinct representations can be envisioned, for the neutral zone position in chimneyless homes, for air infiltration to occur. Figure 1 shows the case when the absolute level of wind, the indoor-outdoor temperature difference, and the relative wall permeabilities are such that both the windward and leeward neutral zones are within the structure.

Similarly, Figure 2 illustrates the case when the windward wall zone is above the structure and the leeward wall neutral zone is within the structure. Figure 3, on the other hand, shows the reverse case (windward zone within and leeward zone without the structure), and Figure 4 the case when both zones are outside the structure. For homes equipped with a chimney, and with the furnace operating, a similar set of representations exist, one of which is shown in Figure 5.

It has been the objective of the modeling effort to provide a tool that allows the determination of the exact locations of the neutral zone in each case (and, therefore, of the rate of air infiltration) by using the basic properties of the structure and weather data. For each case shown in Figures 1 through 5, the mass balance formulations around the structure are obtained by equating infiltration and exfiltration above and below the neutral zone.

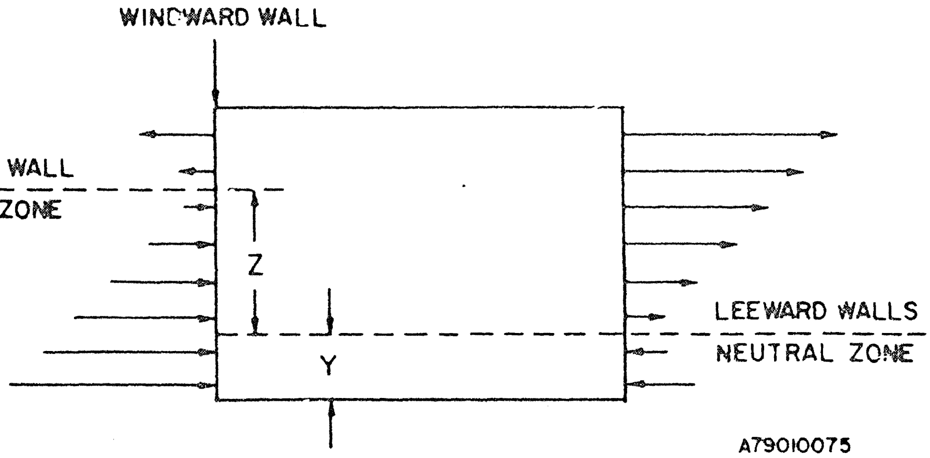


Figure 1. BOTH WINDWARD AND LEEWARD WALL NEUTRAL ZONES INSIDE THE HOUSE

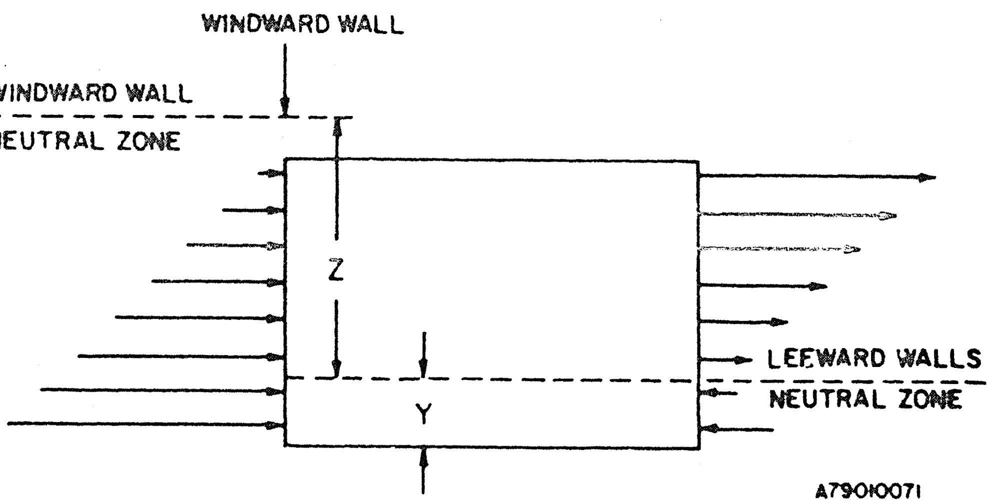


Figure 2. WINDWARD WALL NEUTRAL ZONE ABOVE HOUSE, LEEWARD WALL NEUTRAL ZONE INSIDE HOUSE

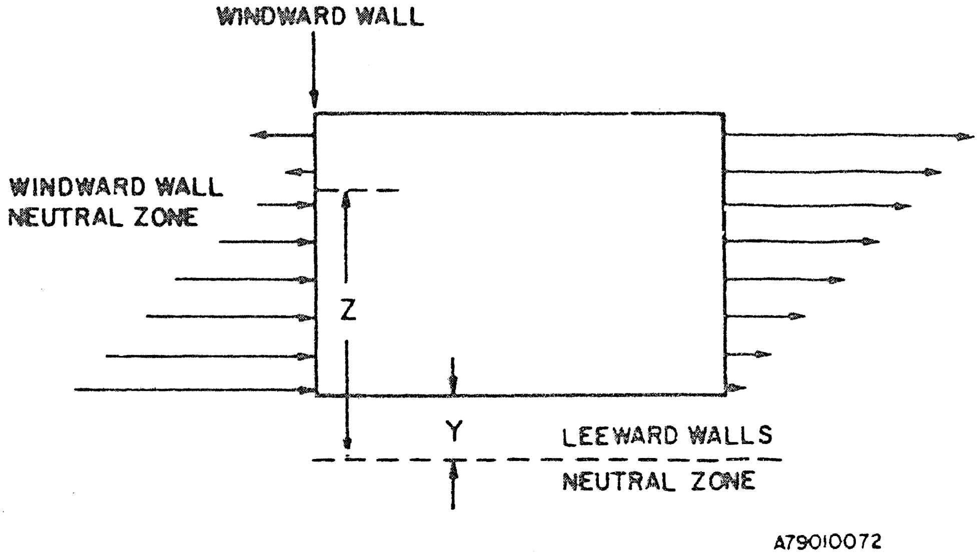


Figure 3. WINDWARD WALL NEUTRAL ZONE INSIDE HOUSE, LEEWARD WALL NEUTRAL ZONE BELOW HOUSE

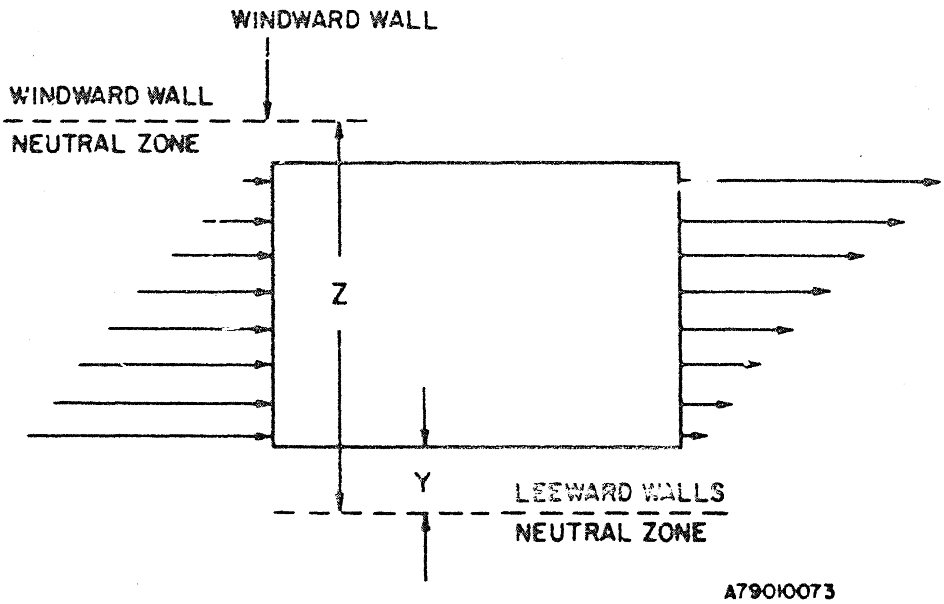


Figure 4. BOTH WINDWARD AND LEEWARD NEUTRAL ZONES OUTSIDE THE HOUSE

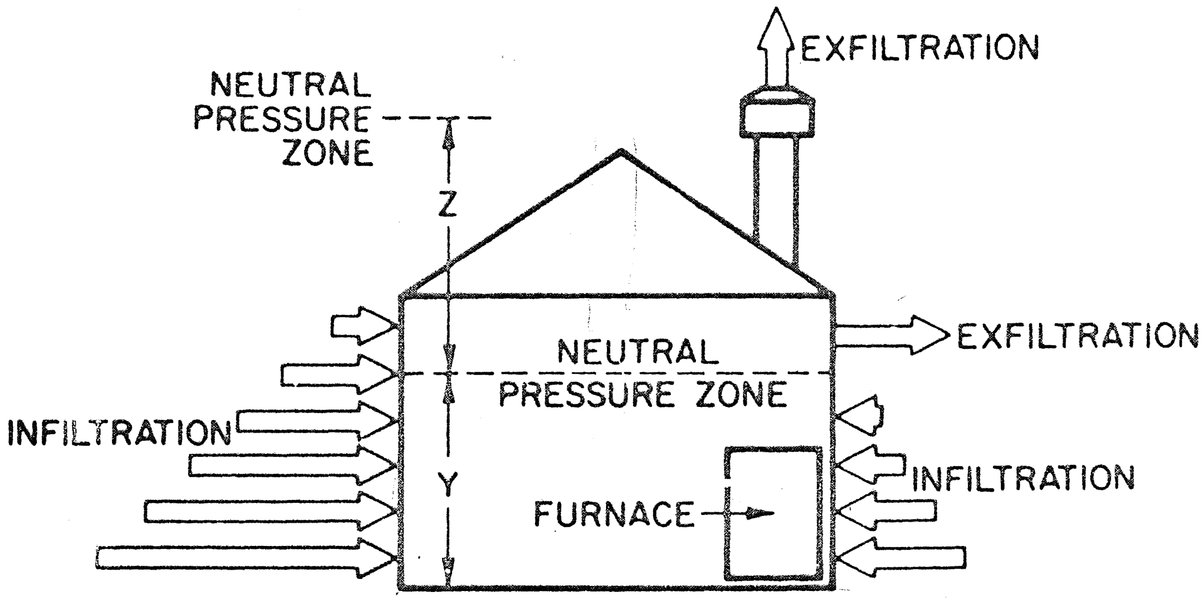


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Figure 5. WHEN WIND, STACK AND FURNACE OPERATION CONTROL AIR INFILTRATION

Each such formulation represents a complex non-linear mass balance equation and the following simplifying assumptions were necessary in order to obtain the required solutions:

- The pattern of crackage is uniform across a wall
- The air flow through a crack is proportional to the 0.50 power of the air pressure differential
- The wind pressure force on the windward walls is positive and does not cause any pressure disturbances on the other walls
- For winds that are not perpendicular to a wall of the house, the wind pressure effect is the cosine of the wind angle (with respect to the walls it acts upon) times the wind speed squared.

Analytically, exfiltration and infiltration across the different zones, as for example those shown in Figure 1, are represented by sets of equations similar to Equation 9, below, for infiltration:

$$\text{Infiltration} = \int_o^Y \Sigma K_x (\overbrace{c\rho_o gh - c\rho_i gh}^{\Delta P})^n \, dh + \int_o^{Y+Z} K_I (c\rho_o gh - c\rho_i gh)^n \, dh \tag{9}$$

and Equation 10 below, for exfiltration:

$$\text{Exfiltration} = \int_o^{H-Y-Z} K_I (c\rho_o gh - c\rho_i gh)^n \, dh + \int_o^{H-Y} \Sigma K_x (c\rho_o gh - c\rho_i gh)^n \, dh \tag{10}$$

where —

H = height of structure

Z = distance between windward and leeward wall neutral pressure zones

Y = distance between house floor and lower neutral pressure zone

h = distance from neutral zone

$\rho_o$ = outdoor air density

$\rho_i$ = indoor air density

g = gravitational constant

c = conversion constant

all in consistent units. Equation 9 also shows that the parenthetic terms in these equations are equal to the $\Delta P$ and that in essence Equations 9 and 10 are integral forms of Equation 6 shown earlier.

The distance Z is determined from Equation 11, relating the wind speed to the density difference between the inside and outside air,

$$Z = \frac{A(WS)^2}{cg(\rho_o - \rho_i)} \tag{11}$$

where —

WS = wind speed

A = conversion constant.

In order to describe infiltration and exfiltration across different zones in homes equipped with a chimney, and furnace operation (for example as shown in Figure 5), in addition to Equations 9 through 11 above chimney flow and energy flow relations are required. These are summarized in Equations 12 and 13 below:

$$F_c = \frac{K_c}{(T_c)^{0.5}} [\Delta P_x + 0.26 \text{ Bh } (\frac{1}{T_o} - \frac{1}{T_c})]^n \tag{12}$$

$$Q = F_c \rho C_p (T_c - 530) \tag{13}$$

where —

$F_c$ = chimney flow, CF/min

$K_c$ = flow coefficient of chimney at standard conditions dependent on vent and system geometry, CF/min-in. $H_2O$

$T_o$, $T_c$ = outdoor and chimney gas temperatures, °R

B = barometric pressure, in. $H_2O$

h = height of chimney, ft

$\Delta P_x$ = indoor-outdoor pressure difference, in. $H_2O$

Q = sensible heat from furnace, Btu/min

$\rho$ = density of flue gas, lb/cu ft (32°F, 1 atm)

$C_p$ = heat capacity of flue gas, Btu/hr-°F (32°F, 1 atm).

Finally, heat transfer (loss) from the chimney is described by Equations 14 and 15 below:

$$T_a = (T_c + T_1)/2 \tag{14}$$

$$F_c\ (T_c - T_1) = (U_a A/\rho C_p)\ (T_a - T_o) \tag{15}$$

where —

$T_c$ = temperature of gases entering chimney, °R

$T_1$ = temperature of gases leaving chimney, °R

$T_a$ = arithmetic average temperature of gases in the chimney, °R

$U_a$ = overall heat transfer coefficient, Btu/hr-sq ft-°F

A = chimney surface area.

### 2.3. Use of the Model and Computer Program

It has been the objective of the modeling effort to provide a tool that allows the determination of the exact locations of the neutral zones in each case (and, therefore, of the rate of air infiltration) by using the basic properties of the structure and weather data. For each case the mass balance formulations around the structure are obtained by equating infiltration and exfiltration above and below the neutral zone. Each such formulation represents a complex non-linear mass balance equation and the following simplifying assumptions were necessary in order to obtain the required solutions:

- The pattern of crackage is uniform across a wall
- The cracks have a uniform resistance to flow regardless of type or location
- The air flow through a crack is proportional to the 0.50 power of the air pressure differential
- The wind pressure force on the windward walls is positive and does not cause any pressure disturbances on the other walls
- For winds that are not perpendicular to a wall of the house, the wind pressure effect is the cosine of the wind angle (with respect to the wall it acts upon) times the wind speed squared.

A computer program has been developed to facilitate the solution of the mass balance equations mentioned earlier and is also being used to provide a measure of validation of the model.

The data required to perform the mass balance model calculations include the following:

- The height of the house
- The crackage length of the windward wall and of the leeward walls
- The indoor and outdoor temperatures
- The wind speed and direction
- Furnace installation parameters
- Furnace operation data.

The program first computes the magnitude of Z (the difference in the height of the neutral zone) and then compares the magnitude of Y (neutral zone height) for each wall against the structure's height (H), in order to define the appropriate case and respective mass balance equation applicable. This program proceeds to set a value for Y for the leeward wall(s) at its lowest limit possible and to increase this value progressively, in small increments, until the mass balance between infiltration and exfiltration is satisfied. The output, then, of the program is the height of the neutral pressure zone on the leeward wall(s) from ground level. Using this value of Y, effective crack length, shielding, and permeability factors for the entire structure, the air infiltration rate is computed as a function of weather.

## IGT MODEL REFINEMENT

In addition to the basic model formulation, presented earlier, there are several practical factors that require delineation, in order to complete the model. For this purpose, we continued the development of limited field data in the "intensive" and "extensive" IGT field homes and acquired unpublished air infiltration data, by liaison with other investigators. We have used all the data, mentioned above, in order to develop appropriate submodels and sub-routines describing the effect of several practical factors on house air infiltration.

1.0 Field Test Data (1979)

We continued the development of limited field data during the report period, by testing both in the "extensive" and "intensive" test homes in support of the model refinement effort. Tables 1, 2, and 3 summarize the data obtained in the three intensive homes, and Table 4 summarizes the data measured in four extensive field-test homes.

In addition we have obtained several portable wind speed indicators to be used for field measurements and onsite recording. We have used these indicators to make measurements of the wind shielding effect at several of the test homes so that a wind shielding factor can then be incorporated in the computer model.

2.0 Field Test Data From Other Sources

In parallel to, and in order to aid, the analytical development of the basic air infiltration model, we developed an air infiltration data base consisting of information obtained by IGT in over 20 field test homes (located in the Chicago Metropolitan area) and data of other investigators made available to IGT for this development. Specifically, the data and sources are:

- IGT Field Test Data

  Over a two year period beginning in 1977, as part of the A.G.A. project HC-4-33, IGT conducted testing and measurements in a total of 23 homes.[19] These measurements included intensive measurements in three homes, and extensive measurements in the other 20 test homes. One intensive test home was unoccupied while the other two and all of the extensive test homes were occupied. The group included a wide variety of type of construction and house age and all were equipped with central gas-fired furnaces.

- Canton Test Homes

  We also utilized data on file at IGT for the Canton Gas and Electric test homes.[20] The data included air infiltration measurements, weather data, and measurements of other house operating parameters obtained over a two year period (furnace and other appliance operation, door openings, vent-fan operation, etc.).

- Princeton Townhouses

  We used air infiltration data for two townhouses from the Twin Rivers development supplied to IGT by Nick Malik, presently of the firm of Gamze-Korobkin-Caloger of Chicago.[10] These data were obtained as part of Dr. Mal 's Ph.D. dissertation at Princeton University and include continuous measureme of air infiltration rates, door closures, weather data, and gas furnace operation.

Table 1. INFILTRATION DATA FROM THE INTENSIVE RANCH TEST HOME

| Run No. | Avg. Wind Conditions Speed, mph | Direction | Avg. Temperatures In | Out | Infiltration Rates, air changes/hr: Blower On Stack Closed | Blower On Stack Open | Furnace On |
|---|---|---|---|---|---|---|---|
| 17 | 3 | Southeast | 80 | 76 | 0.093 | 0.13 | 0.21 |
| 18 | 5 | Southeast | 77 | 77 | 0.20 | 0.33 | -- |
| 19 | 2 | South | 67 | 72 | 0.18 | 0.29 | -- |
| 20 | 5 | South | 72 | 73 | 0.18 | 0.25 | -- |
| 21 | 3 | South | 80 | 85 | 0.25 | 0.22 | 0.42 |
| 22 | 2 | Southwest | 75 | 80 | 0.20 | 0.24 | 0.33 |
| 23 | 2 | Southeast | 69 | 60 | -- | 0.22 | -- |
| 24 | 4 | Northwest | 69 | 69 | 0.22 | 0.26 | 0.40 |
| 25 | 5 | Southeast | 65 | 69 | 0.13 | 0.25 | -- |
| 28 | 5 | Northeast | 70 | 56 | 0.15 | 0.25 | 0.43 |
| 30 | 3 | North | 70 | 52 | 0.11 | 0.31 | 0.40 |
| 31 | 7 | South | 70 | 63 | 0.29 | 0.42 | 0.40 |
| 33 | 6 | West | 70 | 41 | 0.26 | 0.42 | 0.50 |
| 37 | 8 | Southwest | 64 | 27 | -- | 0.42 | -- |
| 39 | 3 | South | 66 | 33 | 0.29 | 0.31 | -- |
| 41 | 5 | South | 62 | 32 | -- | 0.37 | -- |
| 46 | 3 | South | 70 | 32 | 0.297 | 0.37 | 0.50 |
| 48 | 10 | South | 70 | 41 | 0.30 | 0.52 | 0.51 |
| 49 | 6 | South | -- | 34 | -- | -- | -- |
| 50 | 11 | West | 54 | 29 | 0.31 | 0.54 | 0.63 |
| 51 | 5 | South | -- | 32 | 0.35 | 0.46 | 0.51 |
| 52 | 7 | South | 69 | 43 | 0.26 | 0.41 | 0.46 |
| 55 | 5 | Southwest | 63 | 7 | 0.38 | 0.48 | 0.64 |
| 58 | 3 | South | 64 | 9 | 0.40 | 0.50 | 0.56 |

Table 2. INFILTRATION DATA FROM THE TWO-STORY TEST HOME WITH INDOOR FURNACE (No. 13)

| Run No. | Avg. Wind Conditions Speed, mph | Avg. Wind Conditions Direction | Avg. Temperatures In | Avg. Temperatures Out | Infiltration Rates, air changes/hr: Blower On Stack Closed | Infiltration Rates, air changes/hr: Blower On Stack Open | Infiltration Rates, air changes/hr: Furnace On |
|---|---|---|---|---|---|---|---|
| 7 | 9 | Southwest | 62 | 10 | 1.0 | 0.78 | 1.08 |
| 8 | 15 | Northwest | 64 | 0 | 1.03 | 0.97 | 1.17 |
| 9 | 4 | South | 62 | 4 | 0.72 | 0.77 | 0.86 |
| 10 | 8 | Southeast | 65 | 17 | 0.88 | 0.61 | 0.76 |

Table 3. INFILTRATION DATA FROM THE TWO-STORY TEST HOME WITH FURNACE IN THE GARAGE (No. 44)

| Run No. | Avg. Wind Conditions | | Avg. Temperatures | | ← Infiltration Rates, air changes/hr → | | |
|---|---|---|---|---|---|---|---|
| | Speed, mph | Direction | In | Out | Blower On Stack Closed | Blower On Stack Open | Furnace On |
| 4 | 15 | Northwest | 68 | 31 | 0.47 | 0.56 | -- |
| 5 | 7 | Northwest | 68 | 27 | 0.39 | 0.46 | -- |
| 6 | 8 | North | 66 | 32 | 0.63 | 0.514 | -- |
| 6A | 8 | Southeast | 66 | 32 | 0.49 | -- | -- |
| 7 | 13 | West | 67 | 35 | 0.49 | -- | -- |
| 7A | 7 | Southwest | 67 | 28 | -- | 0.38 | -- |

Table 4. INFILTRATION DATA FROM EXTENSIVE TEST HOMES

| House Number | Average Wind Conditions Speed, mph | Direction | Average Temperatures In | Out | Infiltration Rates, air changes/hr Stack closed | Stack open | Furnace on |
|---|---|---|---|---|---|---|---|
| 8 | 8 | Northwest | 67 | 46 | 0.29 | 0.31 | 0.35 |
| 2 | 8 | West | 72 | 14 | 0.49 | 0.81 | 1.0 |
| 23 | 13 | South | 70 | 15 | 0.45 | 0.66 | 0.46 |
| 32 | 15 | South | 69 | 14 | 0.59 | -- | 0.72 |

- Ohio State University

  We also used air infiltration data acquired from Robert Blancett of Owens-Corning Fiberglas. These data were obtained as part of a project conducted by Ohio State University for the Electric Power Research Institute[21] and include air infiltration measurements, weather data, furnace operating characteristics, and door closures. Data from this source are available for six homes and three apartments, with the residences equipped with various heating systems.

- Canadian Test Homes

  Detailed air infiltration data, and enclosure permeability data, were reported by Tamura[22] for a single story residence located in Ottawa, Canada. These data cover a one year period of measurements from a house equipped with an oil furnace.

## 3.0 Support Sub-Routine Development

The major objective of the air infiltration model development effort is an accurate but practical model and program that can be used with information readily available for the residence (from house blue-prints and spec sheets, furnace installation parameters, and weather), without the need for testing. To accomplish the stated objective, the basic model formulations presented earlier are supported with additional information about the structure in order to account for other real effects and this is done through the development of several support models.

### 3.1. The "Total" Crackage Model

Our objective in the development of the model, as has been stated, is to produce a practical model that would have as inputs easily measured variables such as outdoor temperature, wind speed and direction. The most easily measured house structure characteristics are the observed window, door and sill cracks. If we assume that these cracks are uniformly distributed along the height of the house, solutions to Equations 3 and 4 can easily be obtained, reducing the amount of complex computer programming and the need to input the exact location of the observable cracks. The test of these assumptions comes in the comparison of the model predictions to the measured infiltration data.

To develop a proper accounting for the total crackage, a sequence of 5 crackage levels are used, termed crack inventory levels 1 through 5, and are as follows —

Table 5. CALCULATED PERMEABILITY COEFFICIENTS FOR THE INTENSIVE RANCH HOME (Chicago-East)

| Run No. | Wind Speed, mph | Wind Direction | $T_o$ °F | Regime | Infiltration Rate CFM | Permeability Coefficient CIL* 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | ← CFM/ft-in $H_2O$ → | | | | |
| 1 | 0 | - | 66 | Buoyancy | 27 | NA | 4.8 | 3.7 | 3.0 | 2.1 |
| 2 | 5 | SE | 78 | Wind | 7 | NA | 0.4 | 0.4 | 0.2 | 0.2 |
| 3 | 2 | S | 67 | Mixed | 14 | 6.6 | 2.4 | 1.7 | 1.3 | 0.9 |
| 4 | 2 | SW | 74 | Mixed | 17 | 6.8 | 2.5 | 1.8 | 1.4 | 1.0 |
| 5 | 2 | S | 60 | Mixed | 11 | 4.0 | 1.5 | 1.1 | 0.9 | 0.6 |
| 6 | 5 | NE | 57 | Wind | 24 | NA | NA | NA | NA | NA |
| 7 | 3 | S | 46 | Mixed | 19 | 4.5 | 1.6 | 1.2 | 1.0 | 0.7 |
| 8 | 3 | N | 58 | Mixed | 17 | 3.5 | 1.2 | 1.0 | 0.8 | 0.6 |
| 9 | 8 | S | 66 | Mixed | 17 | 7.2 | 2.6 | 1.4 | 1.0 | 0.6 |
| 10 | 6 | W | 40 | Mixed | 22 | 2.7 | 1.0 | 0.8 | 0.6 | 0.5 |
| 11 | 2 | S | 33 | Buoyancy | 27 | 4.3 | 1.6 | 1.2 | 1.0 | 0.7 |
| 12 | 4 | S | 30 | Mixed | 29 | 5.1 | 1.9 | 1.4 | 1.1 | 0.8 |
| 13 | 10 | S | 40 | Mixed | 27 | 5.9 | 2.2 | 1.3 | 1.0 | 0.6 |
| 14 | 6 | S | 40 | Mixed | 33 | 6.3 | 1.8 | 1.6 | 1.2 | 0.8 |
| 15 | 11 | W | 34 | Wind | 28 | 2.1 | 0.8 | 0.6 | 0.5 | 0.4 |
| 16 | 5 | S | 33 | Mixed | 19 | 3.4 | 1.2 | 0.9 | 0.7 | 0.5 |
| 17 | 7 | S | 42 | Mixed | 19 | 4.1 | 1.5 | 1.0 | 0.8 | 0.5 |
| 18 | 4 | SE | 8 | Buoyancy | 41 | 5.5 | 2.0 | 1.5 | 1.2 | 0.9 |
| 19 | 3 | S | 8 | Buoyancy | 41 | 5.7 | 2.1 | 1.5 | 1.3 | 0.9 |
| 20 | 8 | N | 30 | Wind | 32 | 2.4 | 0.8 | 0.7 | 0.6 | 0.5 |
| | | | | | AVERAGE | 4.71 | 1.78 | 1.31 | 1.03 | 0.73 |
| | | | | | S. DEV. | 1.59 | 0.95 | 0.68 | 0.57 | 0.39 |

*CIL - Crack Inventory Level

1 Window and door perimeters only
2 Window and door perimeters and framing
3 Window and door perimeters and framing plus sill plate
4 Window and door perimeters and framing plus two times sill plates
5 Window and door perimeters and framing plus four times sill plate.

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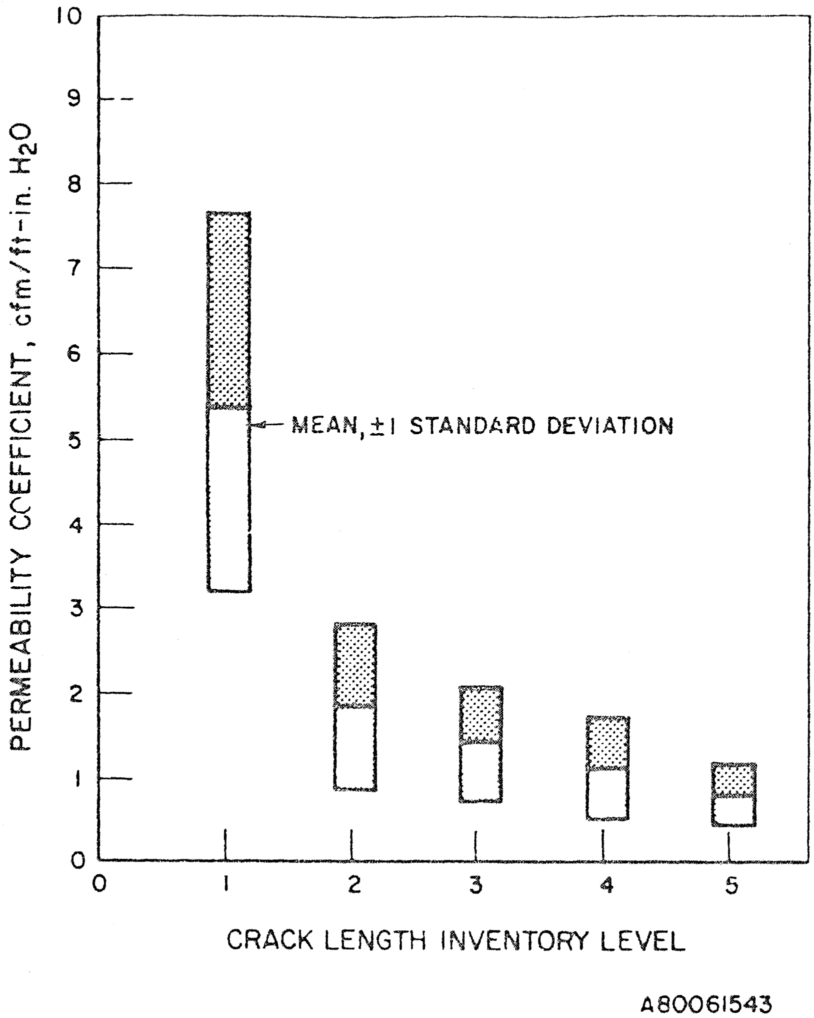


Figure 6. ASSESSMENT OF MODEL FOR "TOTAL" CRACK LENGTH ESTIMATION (FIELD-TEST SITE, "INTENSIVE" RANCH HOUSE, CHICAGO-EAST)

### 3.2. Wind Shielding Model

In the derivation of the air infiltration model equations, it was pointed out that wind speed is an important driving force in determining infiltration rates and that it is extremely important that wind speed levels at the site be known. Generally however, weather data are available from the nearest official weather station and it is usually assumed that outdoor dry-bulb temperatures, and to a large extent, wind direction data from such nearby sources correspond adequately with similar data at the test site. On the other hand, wind speed, and to a lesser extent wind direction, can be severely altered, due to shielding by surrounding structures and trees with foliage.

There is only minimal information in the literature regarding wind shielding factors. Dagliesh and Boyd[24] have attempted to develop conversion factors for changing weather station wind speed to on-site wind speed and Tamura[22] used their model in two test houses and found that the ratios of on-site wind speed to weather station wind speed were 0.65 and 0.56, respectively. Warren[25] has determined that the wind speed profile, under various types of shielding, could be related by the empirical equation:

$$\frac{V}{V_m} = a\ h^b \tag{16}$$

where —

$V$ = wind speed at height h above ground, mph

$V_m$ = wind speed at 10 meters, mph

$h$ = height, meters.

The coefficients a and b have been related to four types of shielding conditions defined as open, country, urban and city, in order of increasing shielding and their values are summarized in Table 6.

Table 6. WIND VELOCITY PROFILES*

| Type of Shielding | Equation Constants A | Equation Constants B |
|---|---|---|
| Open | 0.68 | 0.17 |
| Country | 0.52 | 0.20 |
| Urban | 0.40 | 0.25 |
| City | 0.31 | 0.33 |

*Developed by Warren[18]

The wind speed profiles which represent the extreme (open and city) are illustrated in Figure 7.

Figure 7 also shows the agreement between the Warren typical wind profiles and that computed with Equation 5 for IGT's Canton Field Test Homes from detailed on-site and Canton-Akron airport weather station data, available for March and April 1970. The detailed comparison of the actual wind speed data (on-site to airport) is shown in Figure 8 (3 and 1-hour averages), with the data indicating a shielding factor of about 0.56. It must be noted, however, that the Canton Test Homes were located in an open area (new subdivision) with newly planted trees.

Figure 9 shows the comparison of the Warren predicted wind profiles with data from 4 additional IGT Field Test Homes (Chicago-East, Chicago-South, Chicago-West and Chicago-North). The actual data from these houses show shielding factors even lower than the lowest estimates of Warren (for city dwellings). Further work is needed in order to expand the Warren modeling to cover shielding arrangements such as encountered in the 4 IGT test homes or to develop other alternative approaches to correlate a structure's surroundings with wind shielding effects.

### 3.3. Permeability Correlation

In addition to modeling of total crackage and of the effect of shielding of the wind force on a house, several other effects and characteristic quantities remain to be developed, before general use of the air infiltration model can be made. Of these, development of characteristic permeability coefficients for various typical structures (from gross structural information) is of prior

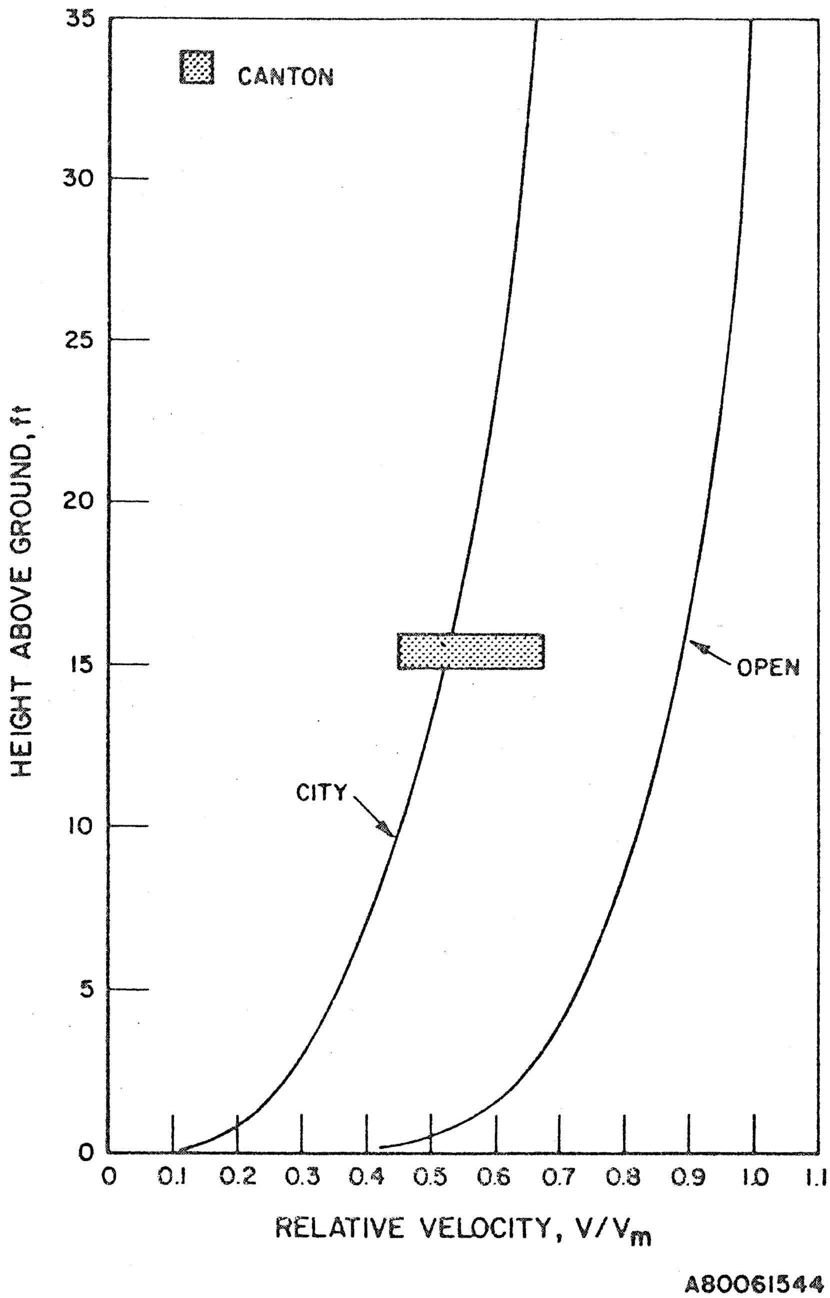


Figure 7. WIND SPEED PROFILES AND SHIELDING DATA FOR THE CANTON FIELD TEST HOMES

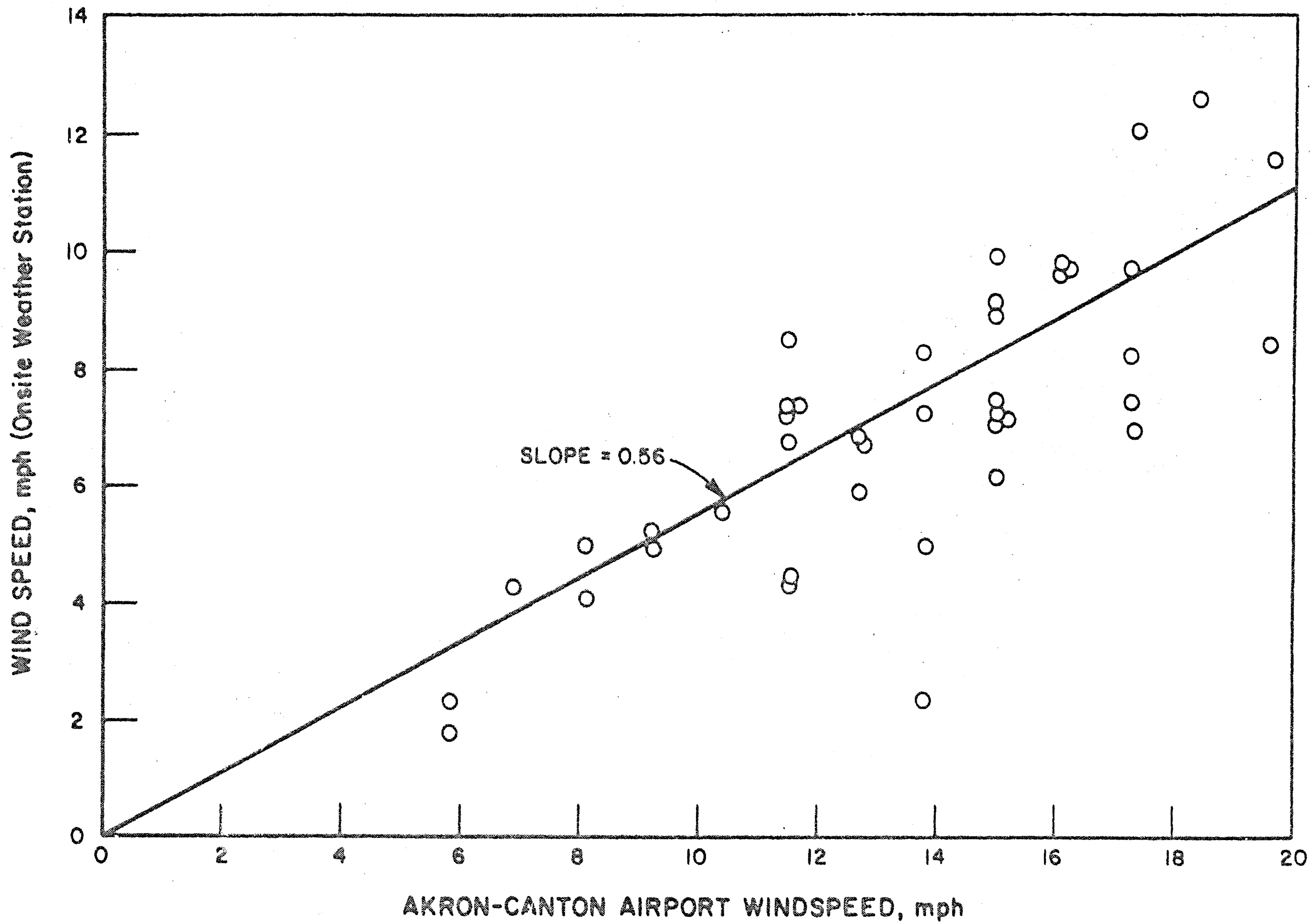


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Figure 8. COMPARISON OF AIRPORT AND ON-SITE WEATHER DATA (Canton Test Homes)

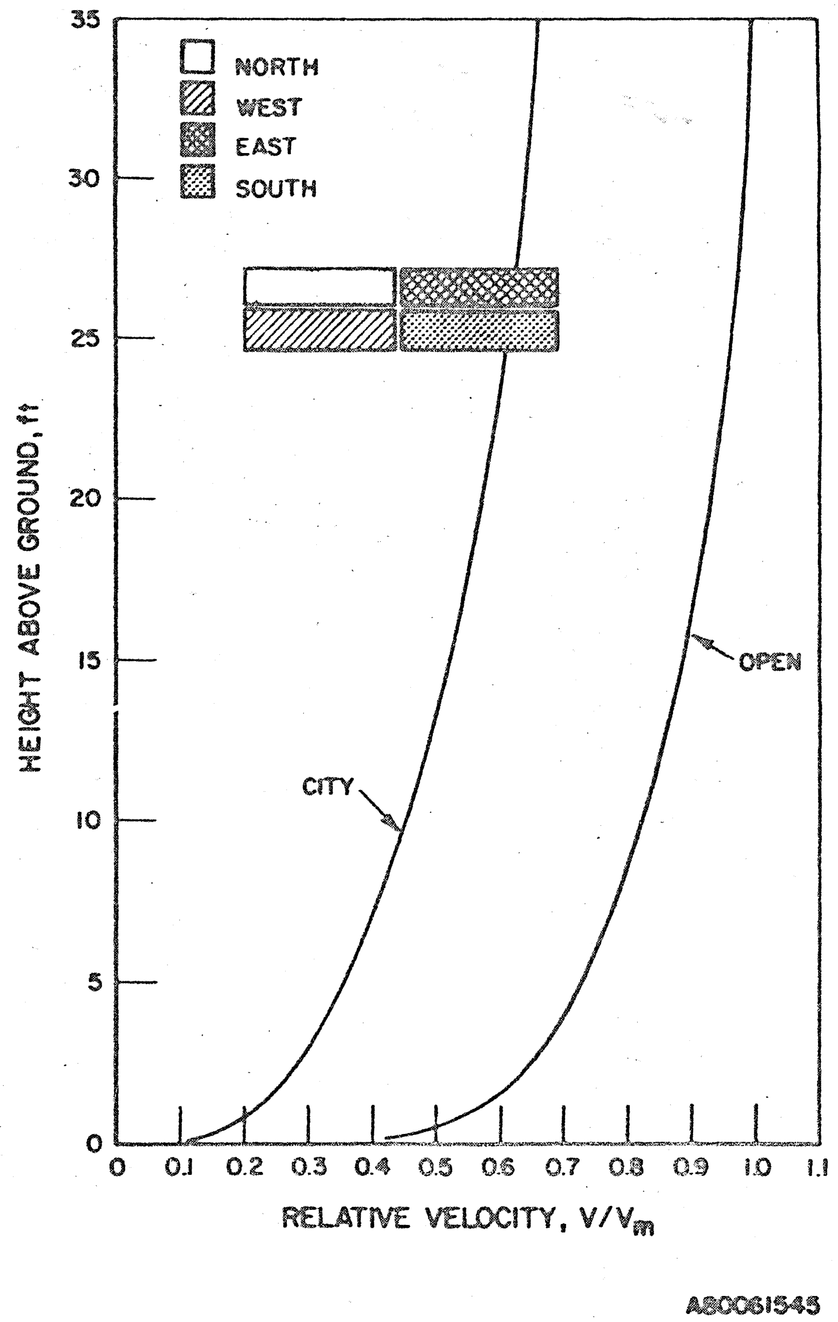


Figure 9. WIND SPEED PROFILES AND SHIELDING DATA FOR 4 CHICAGO FIELD TEST HOMES

importance. We have used the detailed air infiltration data available from several test homes, the total crackage sub-model, and the shielding values, estimated for each home through Equation 16 and actual on-site and weather station data, to compute typical permeability coefficients. A summary of these estimates are presented in Table 7.

It is seen in Table 7 that, generally, permeability coefficients with values around 1.0 tend to be typical of single-story with basement or crawl-space and split-level structures, with or without chimneys. Two story structures with basement (but without chimney) may correspond to coefficients around 1.5, while 2-story structures and higher, with basements and chimneys, may be characterized by permeability coefficients in the range of 2.5 to 3.5.

While the data of Table 7 may be limited, they represent the only information available that begins to provide a systematic, but totally empirical, approach to developing the needed whole-house permeability data. Further work is required to augment the available data with information from other structures or to develop permeability coefficients by totally different approaches.

### 3.4. Vent-Fan Usage and Door Openings

Ways to include the effect of house vent-fan usage and unscheduled door and window openings on air infiltration represent second order refinements of the model and have not been fully addressed to date. Initial tests (using infiltration data for periods during which scheduled fan-usage and/or door openings were programmed) indicate that proper accounting can be made of these effects, given sufficient data on air flow capacities, and schedule of operation typical of actual homes and living habits.

## MODEL VERIFICATION

Part of the data base available to IGT consists of very detailed air infiltration, structural, and furnace operation data from two test homes. These are, a single story house located in Ottawa, Canada equipped with an oil furnace for space heating, and a 2-story frame housing unit in the Twin Rivers Project of New Jersey equipped with a central gas furnace, similar to house No. 11 shown in Table 7. The Canadian house (Tamura Test Home No. 1) was monitored over 3 distinct seasons (winter, summer and winter-

Table 7. PERMEABILITIES OF VARIOUS STRUCTURES

| Test House | Type of Structure | Heating System | Permeability Coefficient |
|---|---|---|---|
| 1. IGT - CHIE | 1-Story Frame with Crawlspace | Gas | 0.74 |
| 2. OSU - SRSG | 1-Story Brick (and Stucco) with Basement | Gas | 1.13 |
| 3. OSU - HSLG | Split Level Frame and Stucco | Gas | 1.12 |
| 4. Canton Test Home | 1-Story Frame with Basement | Electric | 1.20 |
| 5. OSU - KTSC | 2-Story Frame with Basement | Electric | 1.56 |
| 6. OSU - CTSE | 2-Story Frame with Basement | Electric | 1.60 |
| 7. IGT - CHIC | 2-Story Brick with Basement | Gas | 2.30 |
| 8. IGT - CHIW | Split Level Frame with Crawlspace | Gas | 2.53 |
| 9. IGT - CHIS | Raised Ranch Frame with Basement | Gas | 2.65 |
| 10. OSU - HTSG | 2-Story Frame with Basement | Gas | 3.65* |
| 11. TR#1 | 2-Story Frame with Basement | Gas | 3.66 |

* The infiltration rate in this house was very high even when there were no apparent driving forces (i.e., wind, buoyancy).

spring period) during 1960-62, and the Twin Rivers housing unit (Malik Test Home No. 2) in 1974, with usable detailed infiltration data covering the October-December 1974 periods.

We have used IGT's air infiltration model, the support sub-routine for total crackage estimation, shielding factors available from the investigators of these test homes and the permeability data of Table 7 above, in order to project detailed air infiltration data for these houses for comparison to the actual data. We used an average value of 1.0, as the representative permeability coefficient of the Canadian Test Home, and the permeability coefficient (3.66) from Table 7 for the Malik Test Home No. 2, because of the similarity to its companion unit (TR-1).

The comparisons between measured and model estimated infiltration rates for these two test houses are shown in Figures 10 and 11. The measured data cover ranges of weather conditions and furnace operation which caused infiltration rates in the Canadian home to vary by a factor of 4 (from 14 cfm to 56 cfm or from 0.06 air changes per hour to 0.24 air changes per hour) and in the Twin Rivers home by a factor of 2.5 to 3 (from 75 cfm to 205 cfm or from 0.25 air changes per hour to 0.68 air changes per hour).

The data in Figures 10 and 11 show that the model can be used to estimate rates of infiltration in these test homes with reasonable accuracy. Specifically for both test homes, the model predicts the actually measured air infiltration rates within 15 percent of the actual values at a level of confidence over 70% or at one standard deviation. We believe that for practical applications, this level of accuracy is quite acceptable, given the alternatives, but that more effort is required in order to increase the level of accuracy and to extend the model's applicability to other types of structures, climates and evenmore to occupants living styles. At present, the preliminary model and data are being used to develop a dynamic air infiltration load model for general use with residential building energy calculation and load programs.

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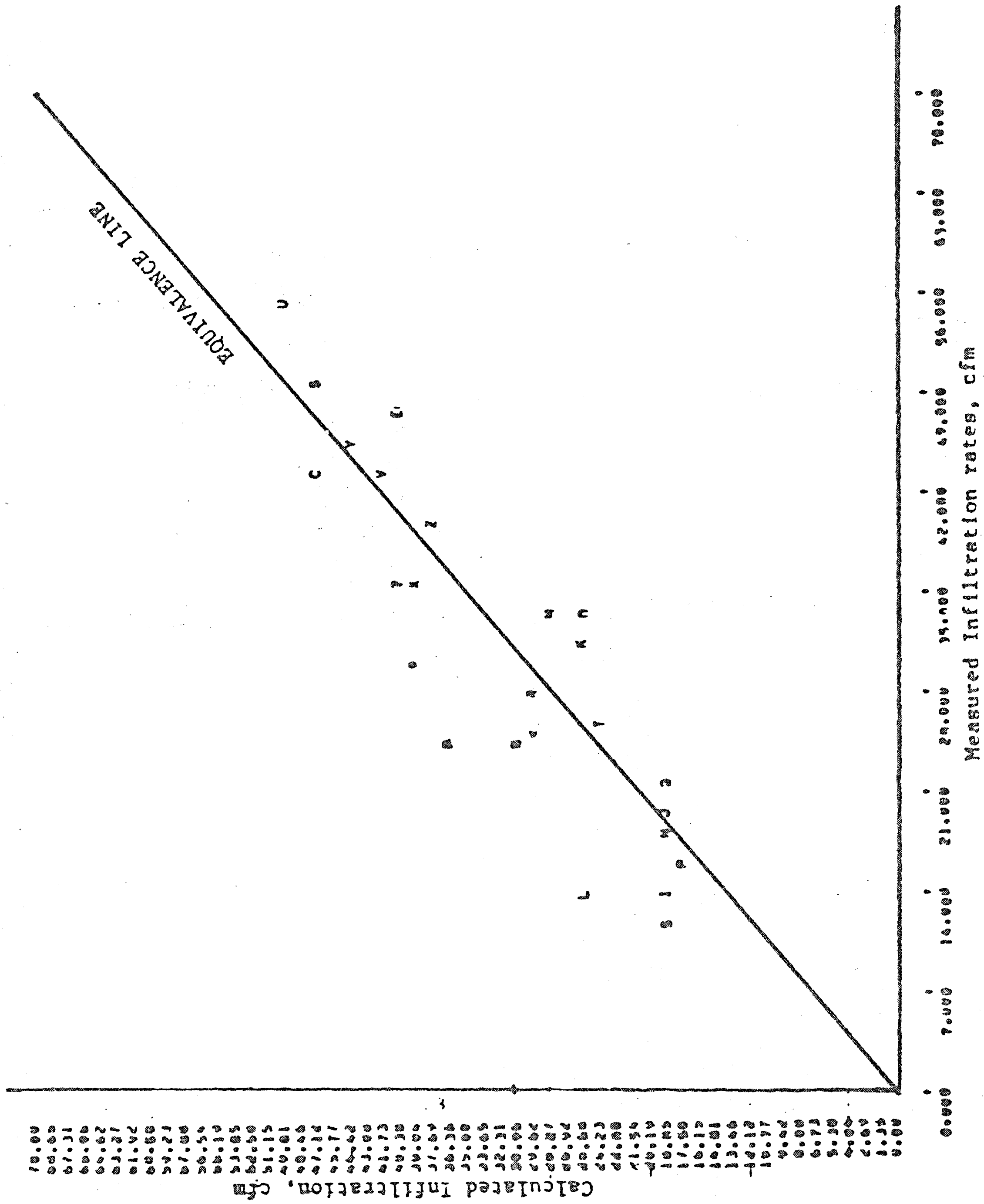


Figure 10. COMPARISON OF MEASURED INFILTRATION RATES IN THE CANADIAN TEST HOME AND MODEL PROJECTIONS

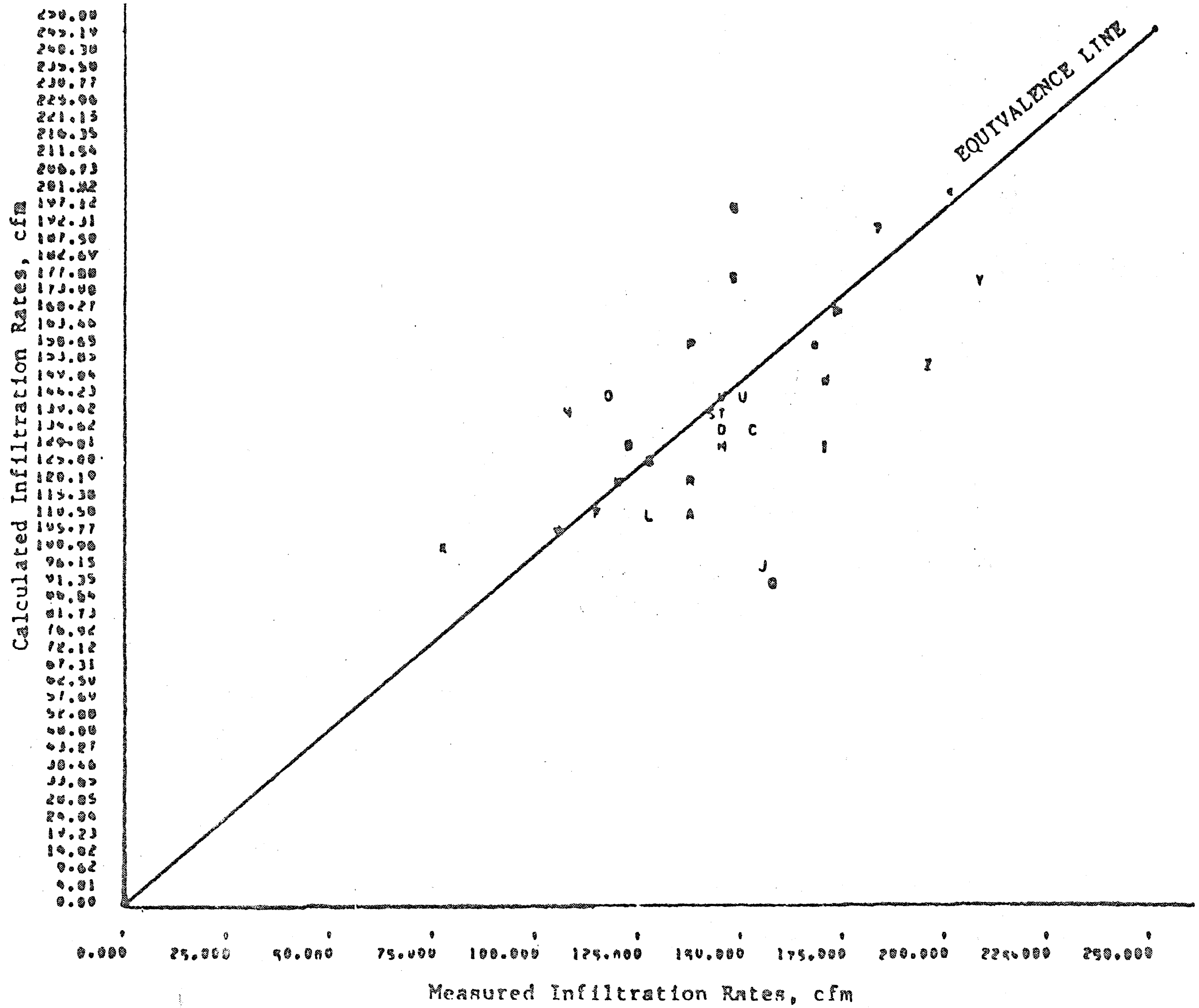


Figure 11. COMPARISON OF MEASURED INFILTRATION RATES IN PRINCETON TOWNHOUSE NO. 2 AND IGT MODEL PROJECTIONS

# CONCLUSIONS AND RECOMMENDATIONS

An air infiltration model for single-family dwellings has been developed that can be used to estimate air infiltration rates within 15% of the measured value, at a confidence level of 70%. The model allows the input of easily measured structure parameters such as total crackage, an empirical permeability coefficient indicative of the width of the crack, and local weather data. In those structures where a gas furnace and chimney are present, the basic furnace-chimney parameters of burner input, vent and chimney size and geometry are also used as input to the model.

A stand-alone computer program has been developed to facilitate the solution of the material balance equations which leads to the actual structure infiltration rate. It is recommended that future work on the model and computer program continue in three areas. One, to fully refine the model and program to include vent-fan usage, door and window openings, and a second chimney for the structures that have fireplace. Second, complete the model verification with data from as many homes (with infiltration data) as possible. Third, modify the model with the aid of a knowledgeable consultant for general use and as a library subroutine for inclusion in general residential building energy programs such as AGA's E-Cube, NBS-LD, DOE-2, etc.

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