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INSTITUTE OF GAS TECHNOLOGY
IIT CENTER
CHICAGO, ILLINOIS 60616

DEVELOPMENT AND FIELD VERIFICATION OF A MODEL OF EXCESS AND HOUSE AIR INFILTRATION FOR SINGLE-FAMILY RESIDENCES

Project 30505 Annual Report 1978

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Jon W. Zimmer
Thomas S. Zawacki
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Date Published — March 1979

Prepared for

GAS RESEARCH INSTITUTE

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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.

During calendar year 1978, this phase of the program covered three major tasks of the program, namely, the conceptual development of an air infiltration model; the development of data, under intensive testing in 3 homes supportive of the model development activity; and the continued monitoring and extensive testing of 23 field homes to obtain data necessary for the verification and fine-tuning of the house-air infiltration model.

Among the accomplishments that have resulted from the 1978 phase of the program, the following are considered worthy of note:

- Several empirical models of house air infiltration, available from the literature, were reviewed and evaluated. Without exception, the limitations, inherent in these models, were found to stem from inadequate accounting of the interactive forces (wind speed and direction, furnace operation, etc.) controlling air infiltration. In general, each of the available models was found to accurately reflect the specific real case used for verification, but extension of the model to other structures and situations was found to be totally inadequate.

- Three test homes were selected to undertake intensive testing in support of the infiltration model development. Of these, the first is a 6 room, ranch-type home, 16 years of age, with a total gross living area of 1128 square feet. It is built over a crawl space, is equipped with a forced-air gas-fired central furnace, and is totally shielded by numerous trees. The second home is a 6 room, two story, all brick home, 30 years of age, with a total gross living area of 1600 square feet and is only shielded on two sides by similar adjacent structures but free of any trees on the front and rear of the house. The third test house is also a 6 room, two-story dwelling, 2 years of age, of frame construction on a concrete slab, with a total gross living area of 2200 square feet, and with shielding only on 2 sides due to adjacent buildings. All of these homes were instrumented with a weather station for recording of outdoor temperature, wind speed, and direction, and other instruments to monitor and measure air infiltration, excess infiltration due to existence of chimney, furnace operation, indoor-outdoor pressure difference, indoor temperature, and vent-fan operation.

- A fair amount of data on house air infiltration and excess infiltration (due to the existence of the chimney in the home) were obtained in the three intensive test homes. The data obtained were sufficient to define the above quantities fully under the following general conditions:

  a) In the absence of forces for air infiltration
  b) In the presence of wind speed forces only, up to 9 mph
  c) In the presence of variable outdoor temperature (down to 35°F) at near calm, and combined with wind speeds below 9 mph.

- An initial house infiltration model and computer program was developed based on a fundamental wall-by-wall mass balance approach. The infiltration model was used to simulate (for verification) the infiltration characteristics of 19 of the 23 field test homes. Good agreement was obtained for the cases when high wind speeds were prevalent. However, at low outside temperatures (and low wind speeds or calm) an adjustment of the structural crack width was required to achieve correspondence with the measured infiltration values.

- A paper, based on the results from this program to date, entitled, "Seasonal Performance Analysis of Central Furnace Installations," was presented at the Third Conference on Documentation and Analysis of Improvements in Efficiency and Performance of HVAC Equipment and Systems, held on October 23-25, 1978, at Purdue University, West Lafayette, Indiana.

Future work on this program is expected to concentrate on the refinement of the initial model of air infiltration, its verification with additional field data under development during the 1978-79 heating season, and preparation of a computer program and user manual to allow general use of the model by home builders, heating contractors, gas companies, consulting engineers, etc.

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OBJECTIVE

The overall objective of this program is to conduct a field and analytical study to develop and verify a model of excess infiltration losses (occasioned by the existence of a chimney and by the operation of the furnace and water heater) in a single- or two-family residence and to develop a more general house air-infiltration model.

INTRODUCTION

In 1974, a comprehensive series of studies was begun at IGT, funded by the American Gas Association (A.G.A.) to quantify the factors affecting seasonal efficiency. As part of A.G.A. Project HA-4-31, the Institute of Gas Technology (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 a 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.

This report summarizes the effort during 1978 which proceeded along two major tasks, namely, development of the IGT model and field testing, to aid the model development and to provide preliminary validation of the model. The former task included the identification, review, and analysis of past modeling efforts and their limitations, definition of the basic mechanisms for air infiltration, the simultaneous modeling of the various interactive forces for infiltration, and testing of the model against the data by means of a computer program.

The second task 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. The results from all these tests also served to provide for a preliminary verification of the IGT "mass balance" air infiltration model.

REVIEW OF EXISTING AIR INFILTRATION MODELS

The flue-loss model, the excess infiltration data and correlations, and the natural ventilation (house air infiltration) data, developed during the 1976 and 1977 phases of the program, are very valuable for the development of the air infiltration model. Before a practical model is developed, however, a firm understanding of the basic mechanisms of air infiltration and a methodology are also required. We conducted a review of the state-of-the-art and identification of the basic mechanisms and interactions between the various forces for infiltration. The results of our analyses are discussed in this section of the report.

A. The Early Models

In contrast to the dynamic models developed for heat transfer by radiation and conduction 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. Current ASHRAE Methods[2]

ASHRAE describes two methods 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.[6,18]

The major limitation of the crack method, however, 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, ΔP, 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; non-windward walls are likely to experience pressure differentials less than 0.02 inch H_2O from the literature data we have seen.

2. Achenbach-Coblentz Correlation[4]

Another approach to the prediction of infiltration rates is based on the empirical Achenbach-Coblentz correlation derived by regression analysis of data from two test homes at the University of Illinois[3] and tested against 10 electrically heated homes in Indiana.[4] The correlation takes the form —

$$I = A + B \times WS + C \times \Delta T \tag{1}$$

where —

I = infiltration rate

WS = wind speed

ΔT = indoor-outdoor temperature differences

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 ΔT. 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 –

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

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)[8]. The constants found in other studies, however, have varied widely as follows:[3,12,13,19]

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

Laschober and Healy[13], 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. As yet, no one has successfully modeled these constants in terms of measurable house structural characteristics, although it should be possible if adequate knowledge of the leakage characteristics of the various building components are known. However, there are more important limitations to the method.

The Achenbach-Coblentz approach assumes that the infiltration rates are directly proportional to ΔT and to WS and that these components are additive; these assumptions are not theoretically tenable. First, the relative dependence of infiltration on ΔT and wind speed changes gradually and continuously, from complete dependence on ΔT 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 two-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.

3. The Princeton Studies

The linear regression equation 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[14] 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[17] (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 certian cases can be subtractive. (Increasing wind results in decreased infiltration driven by indoor-outdoor ΔT or overall infiltration.) 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[7] has suggested the addition of a cross-product term, (WS) (ΔT) to reflect the interactions between the two parameters, i.e. —

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

Such a model has recently been evaluated by Malik[14] 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 townhouse. However, the model appeared to be inadequate for winds of 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 these interactions over the whole range of ambient conditions. Furtnermore, the constants A, B, and C still depend on the structural characteristics of the house and wind direction and must be determined empirically.

B. Mass-Balance Models

1. The Hittman Approach[8]

The proprietary, Correlated Residential Energy Analysis Program developed by Hittman Associates 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[1] 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 ΔT to the driving force, ΔP, 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 $WS/(\Delta T)^{1/2}$. Therefore, because the model does not take into account these interactive effects, the model cannot be accurate over the whole range of ambient conditions.

2. <u>The NRC (Canada) Method</u>

The mass balance approach has already been used successfully by the National Research Council of Canada in developing a FORTRAN IV infiltration model for multi-story commercial buildings, including the effect of stack action and exhaust or pressurization fan action as well as wind pressures[15,16]. Infiltration is calculated by writing the mass balance equations for each floor and each 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.

THE IGT CONCEPTUAL MODELING APPROACH

A. Background

As part of the effort under A.G.A. Project HA-4-31[10] mentioned earlier, we demonstrated, in a preliminary way, that wind-induced infiltration and its interaction with the gas furnace/vent system can be modeled in terms of mass (flow) balance equations for infiltration and exfiltration. In this manner, the effects of the pertinent parameters (permeability characteristics of the structure, wind speed, and direction, and the presence and operation of a gas furnace/vent system) both the overall infiltration and chimney flow can be evaluated. The initial study did not include the effect of house buoyancy because of the experimental difficulty of imposing an indoor-outdoor temperature differential (ΔT) in a test chamber in the laboratory. Thus, the mass balance equation initially derived for the zero ΔT case was —

$$K_i\ (\Delta P_w - \Delta P_x)^n = K_x \Delta P_x^{\ n} + K_c \Delta P_c^{\ n} \quad (6)$$

where —

K_i, K_x, and K_c = flow coefficient for infiltration, exfiltration, and the chimney vent system, respectively

ΔP_w = wind pressure imposed on windward wall

ΔP_x = indoor-outdoor static pressure difference

n = constant between 0.5 and 1.0.

This equation can be solved manually for the case of no furnace operation, $\Delta T = 0$ and $n = 0.5$, to yield exact models for infiltration rates and chimney flow, in terms of the pertinent parameters, WS, K_x, K_i, and K_c, which were confirmed experimentally in the laboratory test room.

The study also introduced an important new concept: The increase in infiltration rate (relative to the infiltration rate of the same structure with no chimney) due to the presence and operation of the furnace vent system is only a fraction, ϕ, of the chimney exfiltration. The fraction, ϕ, depends only on the relative flow coefficients for exfiltration and infiltration (K_x/K_i ratio), in the absence of house buoyancy or furnace operation. With furnace operation (but no house buoyancy), ϕ depends on wind speed as well as K_x/K_i, depending on the relative magnitude of the wind and buoyancy forces.

Use of the concept of φ-value has since been reported[11] and IGT has used it in the preparation of a model of Seasonal Performance Analysis of CEntral Furnace Installations (SPACE-FI) for the U.S. Federal Energy Administration.[20]

B. Basic Mechanisms of Infiltration

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, ΔT
- Fan exhaust or pressurization
- Chimney buoyancy forces generated by ΔT and by furnace operation.

These pressure differentials, ΔP, act upon the various orifices and cracks in the building envelope to produce flow according to classical orifice theory

$$F = \frac{1}{R} \Delta P^n = K \Delta P^n \qquad (7)$$

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
ΔP = 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.[2]

The overall dynamics of infiltration can be described mathematically in terms of a mass (or flow) balance equation, equating the total mass of air infiltration through various orifices with the total mass of air exfiltration through the orifices.

$$I = \Sigma K_i A_i \Delta P_i^{\,n} = \Sigma K_x A_x \Delta P_x^{\,n} + K_c A_c (\Delta P_c)^n \pm F_f \pm K_v A_v \Delta P_v^{\,n} \quad (8)$$

where —

K_i and K_x = the flow coefficients for infiltration or exfiltration through the fixed orifices of the structure

K_c = exfiltration through the chimney

K_v = infiltration or exfiltration through variable orifices such as doors and windows

ΔP_i, ΔP_x, ΔP_v, and ΔP_c = the pressure differentials acting on the orifices

F_f = flow induced by fan

A = area of orifice

Although adequate models exist for predicting the effect of each of the driving forces independently, the overall mass balance model for residential structures has not been described.

1. Effect of Wind Pressure

When a house is subjected to wind forces, in the absence of buoyancy forces or fan operation, the indoor-outdoor static pressure differential, ΔP_x, will increase until the mass flow of infiltration into the windward wall equals the mass flow out through the other walls and sites of exfiltration.

The extent of the pressure increases as derived from the mass balance equation will be:

$$\Delta P_x = \frac{K_i^2}{K_i^2 + (K_x + K_c)^2} \Delta P_w \quad (9)$$

where —

K_i, K_x, and K_c = the flow coefficients for infiltration, exfiltration, and chimney flow

ΔP_w = kinetic wind pressure.

The infiltration rate, I, in turn is given by —

$$I = K_i \, (\Delta P_w - \Delta P_x)^n + K_i \frac{(K_x + K_c)^2}{K_i^2 + (K_x + K_c)^2} \Delta P_w^{\,n} \quad (10)$$

Thus, the dependence of the inside pressure and the infiltration rate on wind speed are in turn dependent on the relative K_x/K_i ratio of the structure. If $(K_x + K_c) = 0$, then ΔP_x will equal ΔP_w, and the driving force for infiltration $(\Delta P_x - \Delta P_x)$ will be zero. If $(K_x + K_c)$ is infinitely large compared with K_i, then ΔP_x will approach zero, and infiltration will be controlled by K_i with a driving force $\Delta P_i = \Delta P_w$.

On the basis of this model, it is possible to estimate the effect of the permeability characteristics of a house on its sensitivity to wind-induced infiltration. Typical results for an electrically heated home with a total volume of 17,500 cubic feet (Canton electric home) are shown in Figure 1. It will be noted that the sensitivity to wind-induced infiltration is maximum at a K_x/K_i ratio of 1.0 (i.e., the ratio of the flow coefficients for exfiltration, K_x, to that for infiltration, K_i). The wind-induced infiltration rates also increase linearly with the overall permeability of the house $(K_x + K_i)$ as would be expected. The range of $K_x + K_i$ values covered also corresponds to the range of permeabilities for 6 real houses, determined experimentally by Tamura.[18] Thus, the K_x/K_i ratio (in one form or another), as well as the total permeability, are important parameters affecting infiltration.

However, the above model, as it stands, does not take into account the negative wind pressure generated on the leeward side of the structure. To do so would require some assumptions as to the aerodynamic drag coefficient of the structure and the proportion of the total exfiltration sites on the leeward wall.

The drag coefficient, C_d, is a measure of the fraction of the total kinetic energy of an air stream converted to force per unit area acting on the structure:

$$\Delta P = C_d \ (0.000\ 48\ WS^2) \tag{11}$$

where ΔP is the sum of the windward and leeward pressures developed and $0.000\ 48\ WS^2$ is the velocity head of the wind, both in inches H_2O. C_d varies from 1.38 for a thin flat plate to 0.74 for a rectangular structure whose length (in the direction of wind) to height ratio is greater than 3.

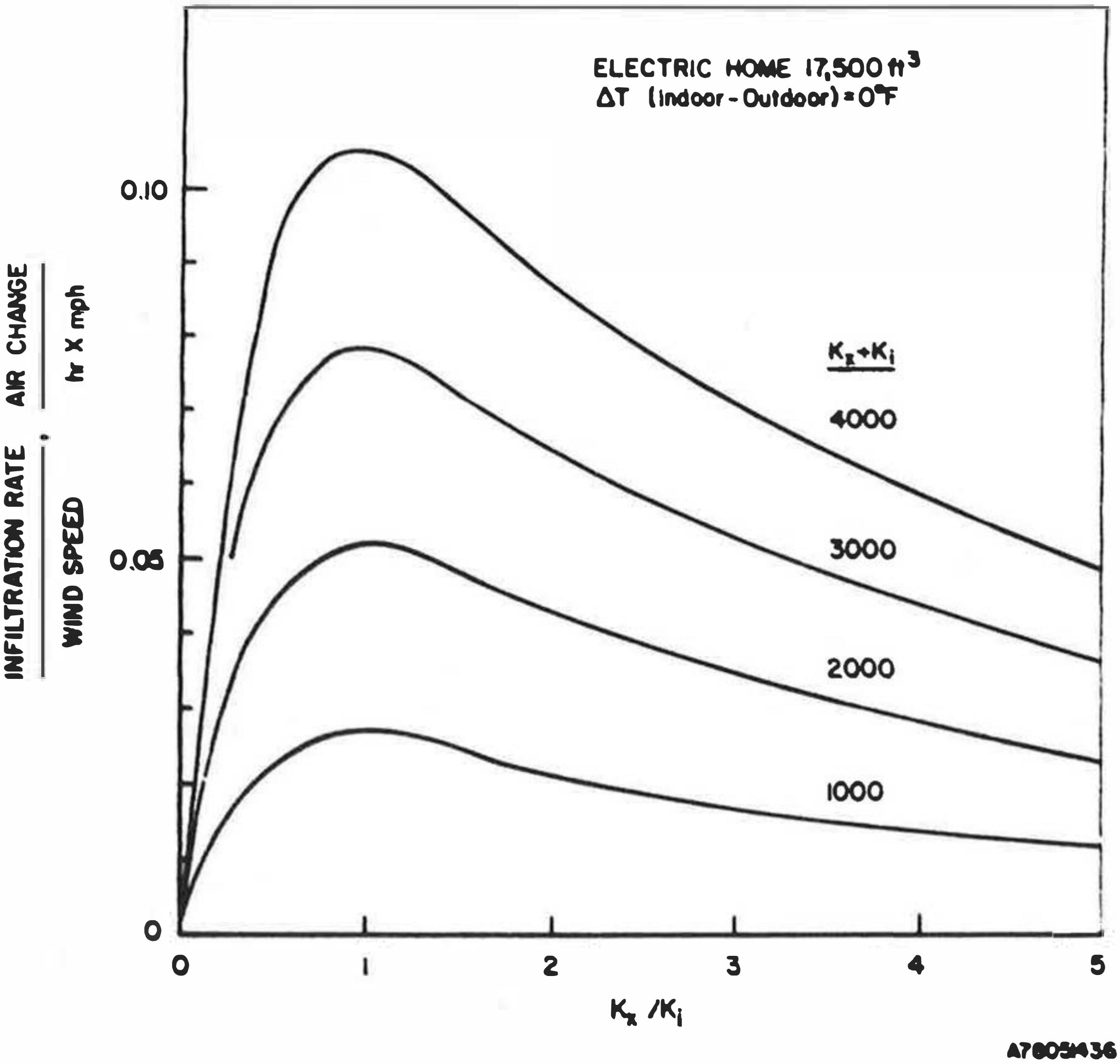


Figure 1. DEPENDENCE OF INFILTRATION RATES ON K_x/K_i RATIO (Calculated)

Exactly how the total drag can be divided into overpressure in front and underpressure in the rea· is difficult to predict. A rule of thumb, however, is to assume that 65% of the total velocity head is exerted on the front of the structure. The negative pressure on the back can then be estimated by subtracting 0.65 from the total drag coefficients. Drag coefficients as low as 0.9 have been measured for two-story houses[5], and we would expect values as low as 0.75 to 0.8 for single-story ranch homes. Thus, the negative leeward wall pressures of about 15% of the velocity head would be expected.

It should be noted, however, that a negative leeward wall pressure has the same effect as increasing the K_x/K_i ratio in that it reduces the inside pressure required to balance infiltration and exfiltration, which, in the last analysis, is the real key parameter. Since characterization of the K_x/K_i ratio of a real home is also inexact and its effect is large compared with that of the negative leeward wall pressure, it may be reasonable to ignore the latter and assume its effect is included in the K_x/K_i effect.

In the absence of house buoyancy factors and furnace operation, the ϕ factor also depends strictly on the K_x/K_i ratio according to the following equation:

$$\phi = \left[1 - \frac{K_i^2 + (K_x + K_c)^2}{K_i^2 + K_x^2}\right]\frac{K_x}{K_c} + 1 \qquad (12)$$

As shown in Figure 2, the wind induced ϕ factor decreases sharply with increasing K_x/K_i, from 1.0 at $K_x/K_i = 0$ to 0.1 at $K_x/K_i = 3.0$.

2. Effect of House Buoyancy

A positive indoor-outdoor temperature difference induces a vertical gradient in the indoor-outdoor pressure difference such that the pressure in the house is greater than outdoors at the top of the house and less than outdoors at the bottom of the house. Thus, outside air infiltrates at the bottom of the house and inside air exfiltrates at the top of the house.

A neutral zone where the inside pressure (p_i) is the same as the outside pressure (p_o) is established at a vertical level above and below which the overall flow coefficients for infiltration and exfiltration are equal so that the mass flow, below the netural zone, equals the mass flow out, above the

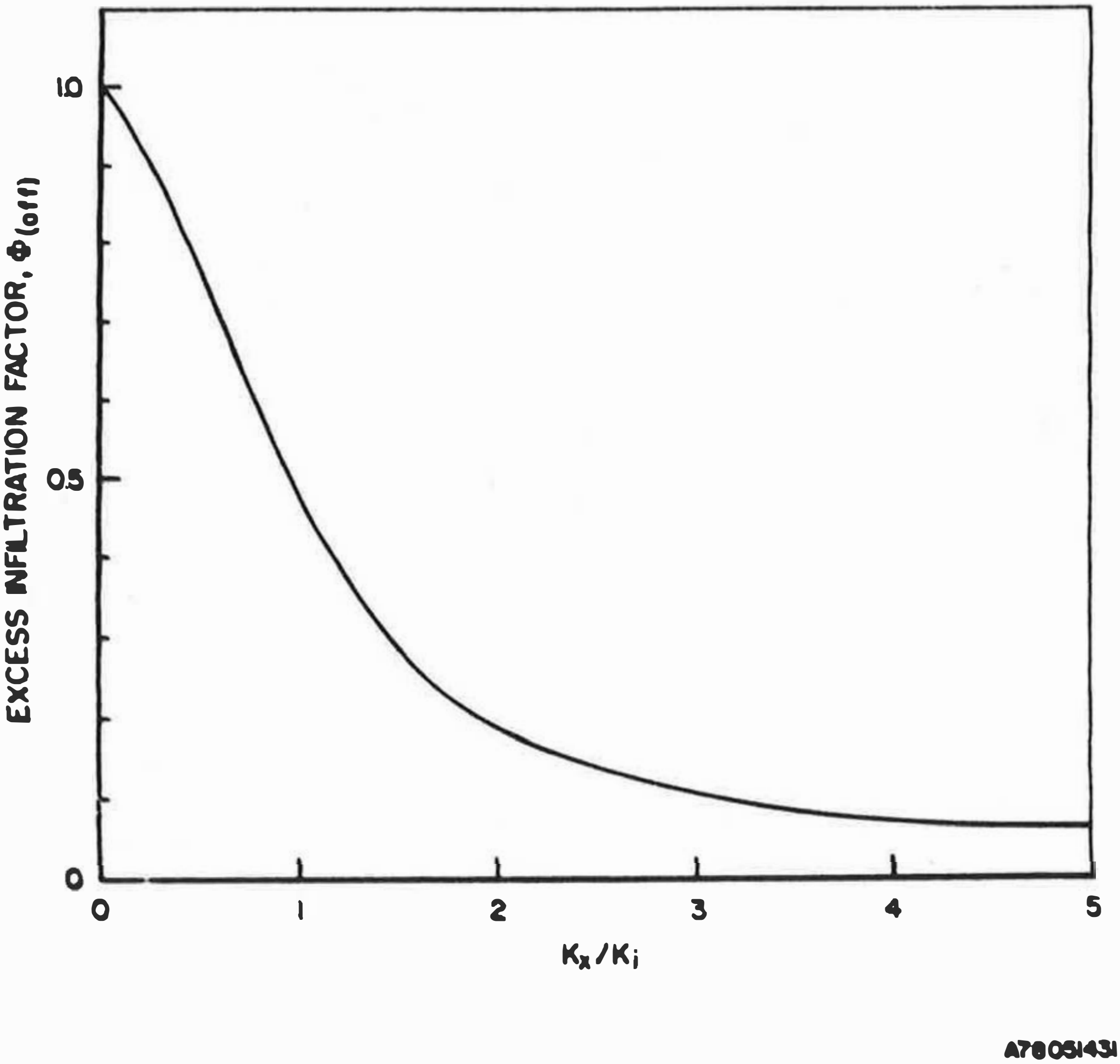


Figure 2. DEPENDENCE OF $\phi_{(off)}$ (Furnace Off) ON K_x/K_i RATIO (Experimental)

neutral zone. In the absence of wind or chimney action, the height of the neutral zone depends only on the vertical gradient in the permeability of the structure. It will also be recognized that in the absence of wind or chimney action, the K_x/K_i ratio will be 1.0.

The magnitude of the pressure gradient depends only on the indoor-outdoor temperature difference, ΔT, according to the following relationship:

$$\frac{\Delta P}{h} = 0.26B \frac{1}{T_o} - \frac{1}{T_i} \quad (13)$$

where —

ΔP = indoor-outdoor temperature differences
h = height above or below the neutral zone
B = Barometric pressure
T_i and T_o = indoor and outdoor temperatures.

3. Infiltration Due to Furnace or Fan Operation

In the absence of wind or house buoyancy effects, the operation of a furnace/chimney system or an exhaust fan induces a slight negative pressure in the whole house. The magnitude of the negative pressure (positive in case of fan pressurization) will be determined by the mass balance between chimney exfiltration and infiltration through the permeable sides in the whole house:

$$F_c = K = K_t \ (\Delta P_x)^n \quad (14)$$

$$F_f = L = K_t \ (\Delta P_x)^n \quad (15)$$

where —

F_c = chimney flow
F_f = exhaust and fan flow
K_t = $K_x + K_i$
ΔP_x = indoor-outdoor static pressure differential induced by fan or furnace operation.

The chimney exfiltration has been modeled[9] as follows(in abbreviated form):

$$F_c = \frac{K_c}{(T_c)^{\frac{1}{2}}} \left[\left(\Delta P_x + 0.26\ Bh\ \left(\frac{1}{T_o} - \frac{1}{T_c}\right)\right]^m \qquad (16)$$

$$Q = F_c \rho C_p\ (T_c - 530) \qquad (17)$$

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

ΔP_x = indoor-outdoor pressure difference, in. H_2O

Q = sensible heat from furnace, Btu/min

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

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

Thus, infiltration rates (and chimney flow rates) can be calculated by the simultaneous solution of Equations 14, 16, and 17.

In the case of exhaust or pressurization fans, Equation 15 alone is sufficient because the induced pressures in the house will have a negligible effect on output.

C. Interactions Between Different Driving Forces

A mass balance model for infiltration, resulting from the combined action of wind, buoyancy, and fan forces, will be complicated by the fact that these forces interact in such a way that changes in the mode of control occur with changes in the relative magnitudes of each force.

1. Furnace Operation and Buoyancy

The buoyancy forces generated by the chimney, particularly with the furnace on, induce a slight negative pressure in the whole house. This does not affect the magnitude of the gradient in the indoor-outdoor pressure gradient, $\frac{\Delta P}{h}$, but does increase the height of the neutral zone. This is illustrated qualitatively in Figure 3 for two-story house, 18 feet in height, with uniformly porous walls. With the furnace off and the chimney blocked, the neutral zone would be at 9 feet; the indoor-outdoor pressure differences

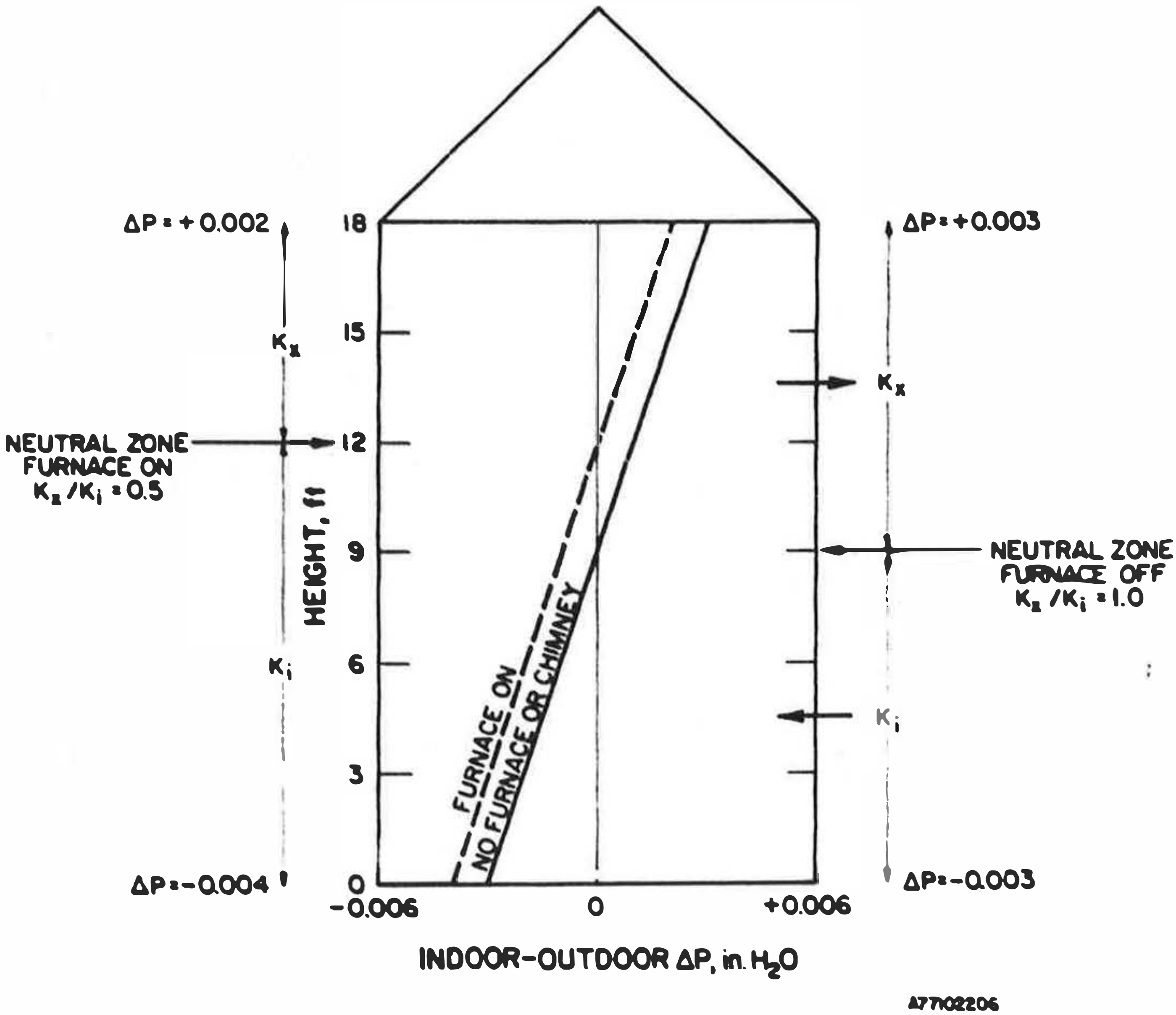


Figure 3. EFFECT OF FURNACE OPERATION ON NEUTRAL ZONE (No Wind)

would be +0.003 in. H_2O (ΔT = 12.5°F) at the top (18 feet), zero at 9 feet, and - 0.003 at the bottom; and K_x/K_i would equal 1.0. With the chimney open and the furnace operating, a slight negative pressure is exerted on the house (assumed to be 0.001 in. H_2O), and the pressure gradient curve is shifted to the left by 0.001 in. H_2O, thus raising the neutral zone from 9 to 12 feet, which, in turn, decreases K_x/K_i from 1.0 to 0.5. Thus, furnace operation (or vent fan operation), which tends to decrease indoor pressure, tends to increase the height of the neutral zone and decrease K_x/K_i.

2. Wind and Buoyancy

When a house is subjected to wind forces, in the absence of house buoyancy forces, the indoor-outdoor static pressure differential (ΔP_x) in the house will increase. The extent of the pressure increase, as derived from the mass balance equation, will be —

$$\Delta P_x = \frac{K_i^2}{K_i^2 + (K_x + K_c)^2} \Delta P_w \tag{18}$$

where —

K_i, K_x, and K_c = the flow coefficients for infiltration, exfiltration and chimney flow, respectively

ΔP_w = pressure equivalent of wind velocity

When a house is subjected to both wind pressure and an indoor-outdoor temperature difference, however, the indoor pressure is determined by a mass balance between wind and buoyancy-induced infiltration and exfiltration. For example, when a wind pressure is imposed on the windward wall, the indoor pressure is increased by an amount, say ΔP_x, at all levels in the house. The neutral zone on each wall, on the other hand, is determined not by the static pressure difference between indoors and outdoors, but by the total pressure drop across that wall, which is equal to the difference between the indoor-outdoor static pressure difference (ΔP_i) and the pressure equivalent of wind velocity (ΔP_w).

In general, the kinetic pressures imposed by wind forces on each of the four walls are different and, therefore, the wind effect on the neutral zone height will be different for each wall. For example, on the neutral side walls (where ΔP_w is assumed to be zero) the increase in indoor pressure results in lowering the neutral zone. On the leeward wall, which is generally subjected to a negative pressure, the neutral zone is decreased even further, because $\Delta P_x - \Delta P_w$ is now positive. On the windward wall, ΔP_w is positive and, therefore, $\Delta P_x - \Delta P_w$ is shifted in the negative direction, increasing the neutral zone. The overall effect of wind pressure, therefore, is to increase the K_i value of the windward wall and the K_x value of the other three walls. At sufficiently large wind speeds, the windward wall is converted completely to infiltration and the other walls to exfiltration.

In conclusion, increasing wind pressure results in a gradual increase of the K_x/K_i ratio from 1.0 (at zero wind speed) to a new value. The latter is determined by the permeability of the windward wall, relative to that of the rest of the house, at a characteristic wind speed determined primarily by the indoor-outdoor ΔT, and the height of the house. This change is also accompanied by a gradual change from buoyancy-induced to completely wind-controlled infiltration above the characteristic wind speed.

3. Wind and Furnace Operation

As noted above, in the absence of furnace operation or house buoyancy forces, the indoor-outdoor static pressure differences (ΔP_x) as well as the infiltration rate, depend on only wind speed and the K_x/K_i ratio; the ϕ value (furnace off) depends on only the K_x/K_i ratio. However, when the house is subjected to wind pressure together with chimney buoyancy generated by furnace operation, ΔP_x (and therefore infiltration) is determined by the mass balance between wind and buoyancy-induced infiltration and exfiltration. Laboratory studies[10] have shown that at wind speeds above about 10 mph, wind forces predominate and the ϕ values can be seen (Figure 4). Unfortunately, the accuracy of the laboratory measurements were sufficient to delineate these interactions at very low wind pressures, although the existence of a wind-dominated, a buoyancy-dominated, and a mixed wind-buoyancy regime could be inferred.

To further delineate these interactions, we have now made a few preliminary calculations of the combined effect of wind and furnace operation on ΔP_x infiltration ϕ values via a simplified mass balance equation that assumes the chimney exfiltration due to furnace operation is a constant 39 CF/min. This assumption introduces only a small error at the low wind speeds of interest. Other assumptions include a K_x/K_i ratio of 1.0 and $K_x + K_i = 990$

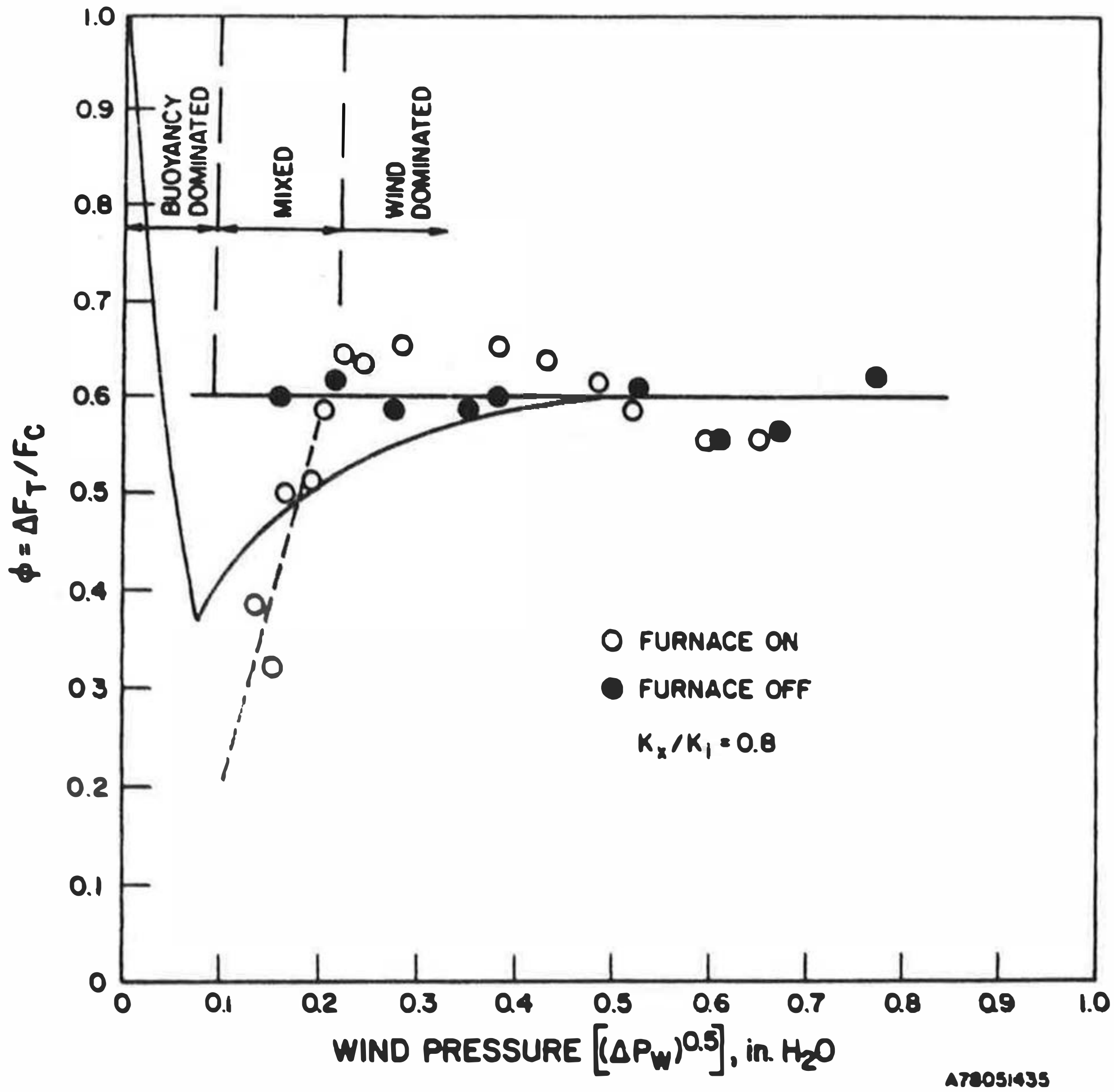


Figure 4. EFFECT OF WIND SPEED AND FURNACE OPERATION ON ϕ FACTOR

CF/min-(in. $H_2O)^{1/2}$. The equations are as follows:

$$I \text{ (Stack Closed)} = K_x \, \Delta P_x^{1/2} = K_i \, (\Delta P_w - \Delta P_x)^{1/2} \quad (19)$$

$$I \text{ (Furnace On)} = 39 + K_x \, \Delta P_x^{1/2} = (\Delta P_x - \Delta P_x)^{1/2} \quad (20)$$

Equation 15 is easily solved because ΔP_x, in the absence of buoyancy forces is defined only by wind pressure and by K_x/K_i (i.e., $\Delta P_x = 0.5 \, \Delta P_w$ for $K_x/K_i = 1$). The solution of Equation 20 can be reached only by successive approximations in which ΔP_x is varied until mass balance is achieved.

These calculations confirm the existence of the different control regimes (Figure 5) and further define the range of wind speeds in which each is operative:

- **Buoyancy Dominated Regime:** ϕ decreases sharply with increasing wind speed from 1.0 at zero at a minimum value at wind speed where the wind is just sufficient to overcome the indoor vacuum created by the furnace operation. The minimum ϕ value also decreases sharply with increasing K_x/K_i ratio by approaching zero at K_x/K_i values greater than 2.
- **Mixed Buoyancy-Wind-Regime:** in which further increases in wind speed result in increasing ϕ, which approaches asymtotically the K_x/K_i dependent value determined for no-furnace operation.
- **Wind Dominated Regime:** complete wind domination does not occur mathmetically, except at infinite wind speed. However, for all practical purposes, it does occur at wind speeds greater than 10 to 15 mph. The calculations do suggest that, in the absence of house buoyancy, $\phi_{(on)}$ will be somewhat less than $\phi_{(off)}$ even at high wind speeds.

D. Modeling All Forces Simultaneously

In a real life situation, the indoor-outdoor pressure differential, ΔP_x, at any point in the house, is determined by the interactions between all forces involved at mass balance for the whole house. Because indoor-outdoor temperature differences impose a vertical pressure gradient, the ΔP_x will vary with height in the house. If the doors between rooms on the same level and between levels in the house present an appreciable resistance to flow (as when shut off), the ΔP_x may vary from room to room on the same level, and the vertical gradient in ΔP_x may be altered. (One such case has already been observed during the field measurements reported in the next section.)

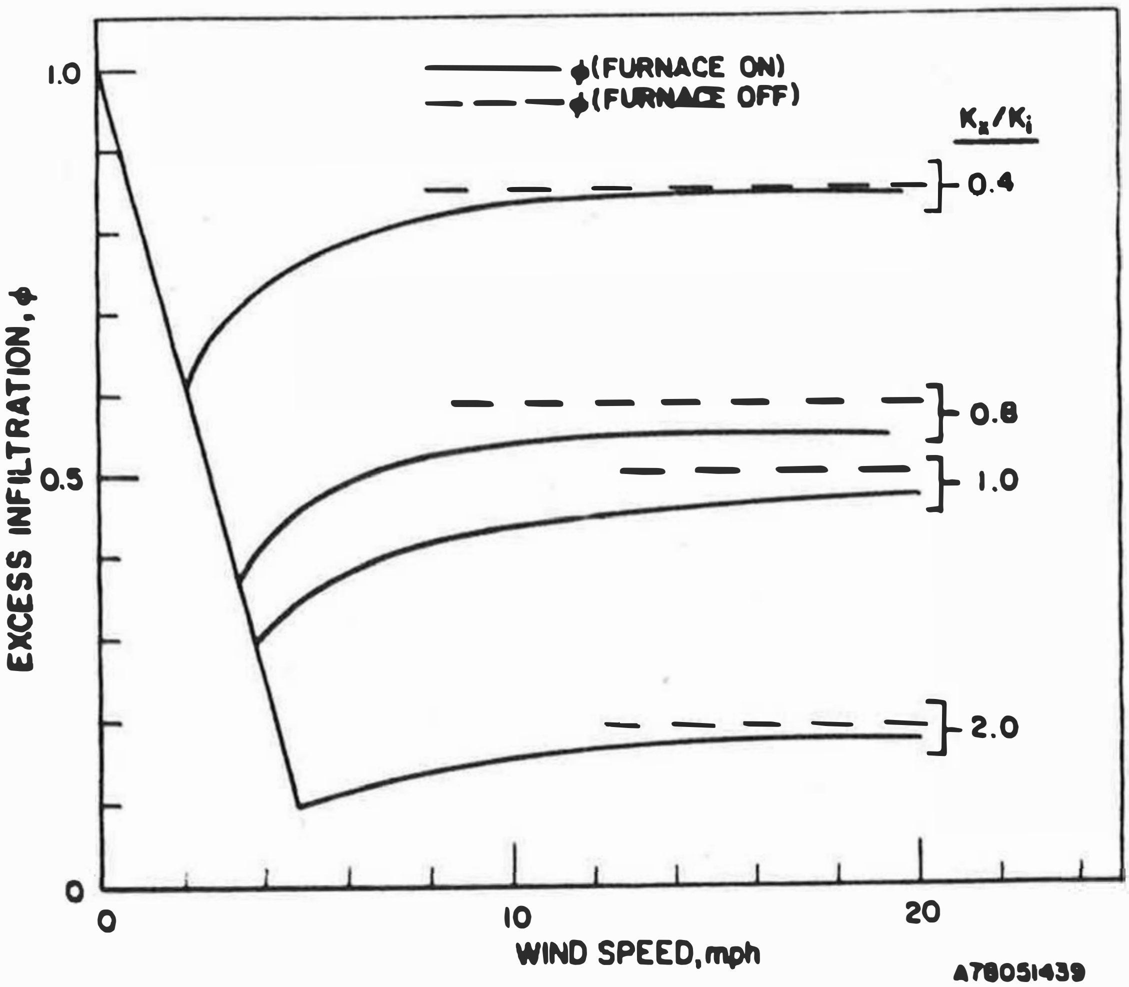


Figure 5. INTERACTIVE EFFECT OF WIND SPEED AND FURNACE OPERATION ON φ VALUES (Zero Indoor-Outdoor Temperature Difference)

In addition, the wind pressures imposed on the outside of the house vary with wall orientation to the wind direction. Therefore, the actual pressure drop across an orifice ($\Delta P_w - \Delta P_x$) that drives the flow through that orifice would vary with height and wall orientation and may vary from room to room at the same height and wall orientation. As a result, precise modeling of a real house becomes difficult without simplifying assumptions.

In order to approach the general effect of the interactions between wind and house buoyancy forces, we developed a simplified, preliminary mass-balance model for infiltration into a two-story home based on the following simplifying assumptions:

- No chimney
- Uniform permeability of all four walls
- Zero resistance to flow between rooms or floors.

These assumptions made it possible to define models for the neutral zone height of the house and for the average ΔP_x across the infiltrating and exfiltrating portions of each wall, in terms of weather parameters.

These models permit the calculation of the infiltration rates for the house assumed above by the method of successive approximations. This involves assuming a value for ΔP_x for each specified combination of wind speed and indoor-outdoor temperature difference to calculate the total exfiltration and infiltration. If equality is not achieved, new values of ΔP_x are assumed until equality is established. The results of such calculations for a two-story house 18 feet in height with uniformly porous walls ($\frac{K}{n}$ = 110; $K_x + K_i$ = 18 X 110 = 1980; K_x/K_i - 3.0) is shown in Figure 6.

On the other hand, the permeability of the walls of real residential structures is highly nonuniform vertically and horizontally. It tends to occur in discrete components (such as windows and doors) at discrete locations. Furthermore, it may ultimately be possible to characterize the leakage characteristics of the individual components and therefore may be more appropriate to define the infiltration model on a floor-by-floor basis, or ultimately, on a component-by-component basis.

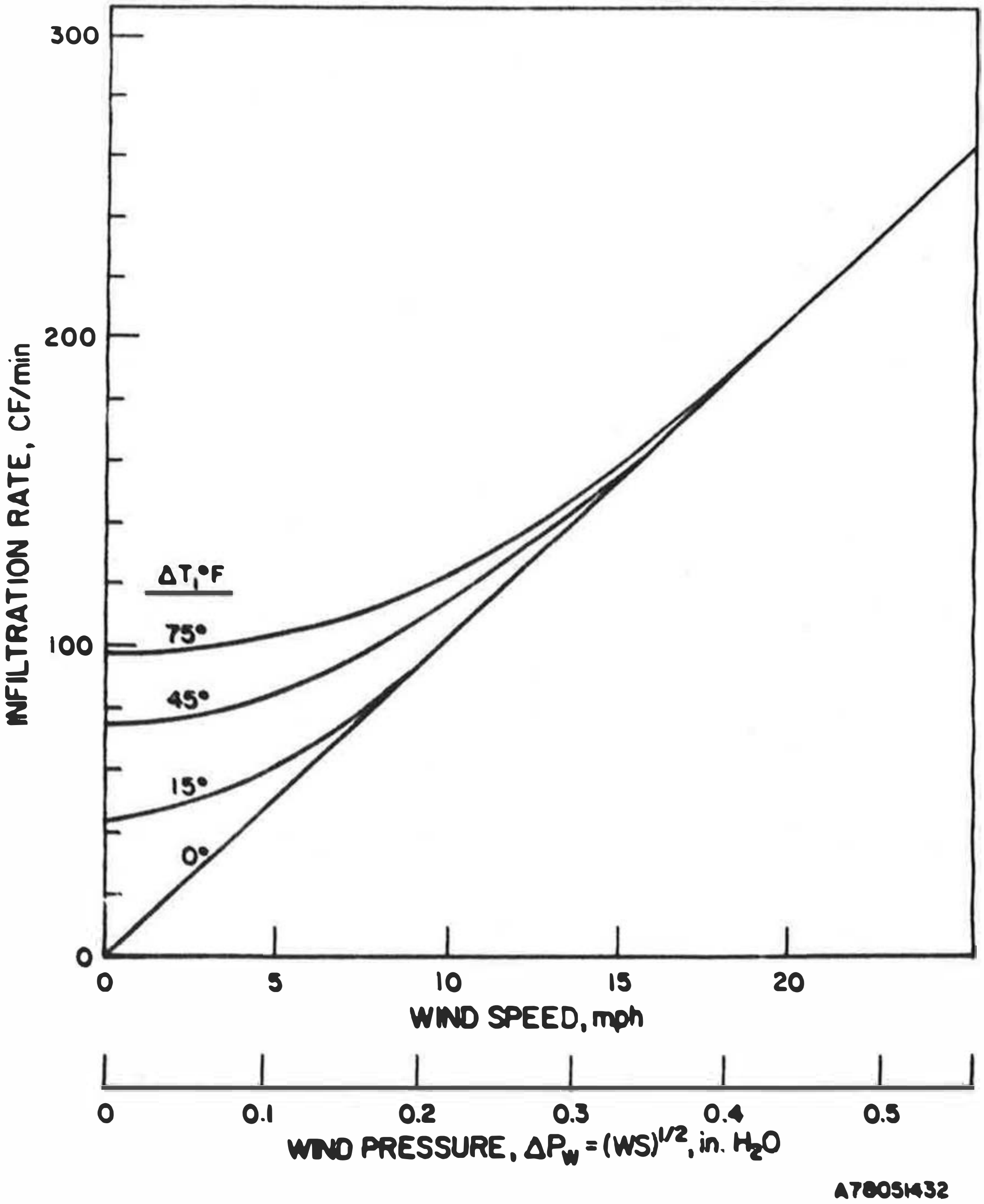


Figure 6. INTERACTIVE EFFECT OF WIND PRESSURE AND INDOOR-OUTDOOR TEMPERATURE DIFFERENCE ON CALCULATED INFILTRATION FOR A CHIMNEYLESS HOME

The National Research Council (Canada) program for multistory buildings[15,16] was set up on a floor-by-floor basis with the assumption that the pressures, flows, and leakage opening all occur at mid-height of each story. This is the simplest approach programwise and should be reasonably valid. In the long run, however, a component-by-component basis may yield more useful information because it would permit the comparative evaluation of the contribution to overall infiltration of equivalent components at different locations (vertically and with respect to prevailing wind direction) on a seasonal basis.

EXPERIMENTAL SUPPORT PROGRAM

In addition to the model development task discussed earlier, this report covers IGT's effort in two other parallel tasks supportive of the model development effort. Both tasks involve testing and measurements in instrumented homes ("intensive" testing) and in over 20 field home ("extensive" testing) in the Chicago Metropolitan area. Measurements carried out in both groups of homes were aimed at providing necessary inputs to model development or to verify the predictive ability of the model.

A. Intensive Field Testing

1. Single-Story Dwelling

Three test homes were selected to undertake "intensive" testing in support of the infiltration model development. Of these, the first is a 6 room, ranch-type home, 16 years of age, with a total gross living area of 1128 square feet. It is built over a crawl space, is equipped with a forced-air, gas-fired central furnace, and is totally shielded by numerous trees.

a. Test Dwelling Description

The single-family (one-story) dwelling is of frame construction with painted masonite siding, Figures 7 to 10. Although this dwelling is approximately 16 years old, based on the appraiser's observation of the improvements, it is considered to have an effective age of approximately 8 years. The dwelling has a poured concrete foundation and is built over a crawl space. The overall dimensions of the dwelling are approximately 24 x 44 feet with an additional entryway having dimensions of approximately 6 x 12 feet. The subject dwelling contains a total gross area of approximately 1128 square feet.

The test home has six rooms, three of which are utilized as bedrooms. (See Figure 11). With the exception of the bath and kitchen areas, which are tile covered, the remainder of the house consists of hardwood floors, except for the southeast bedroom and front entry, which are covered by indoor/outdoor carpeting. The kitchen area is improved with wood built-in cabinets, a range hood, plastic-tile-covered walls, a built-in dishwasher, and a double stainless steel sink. The bathroom area contains a tub with shower, a standard lavatory, a water closet, and plastic tile wall covering. The

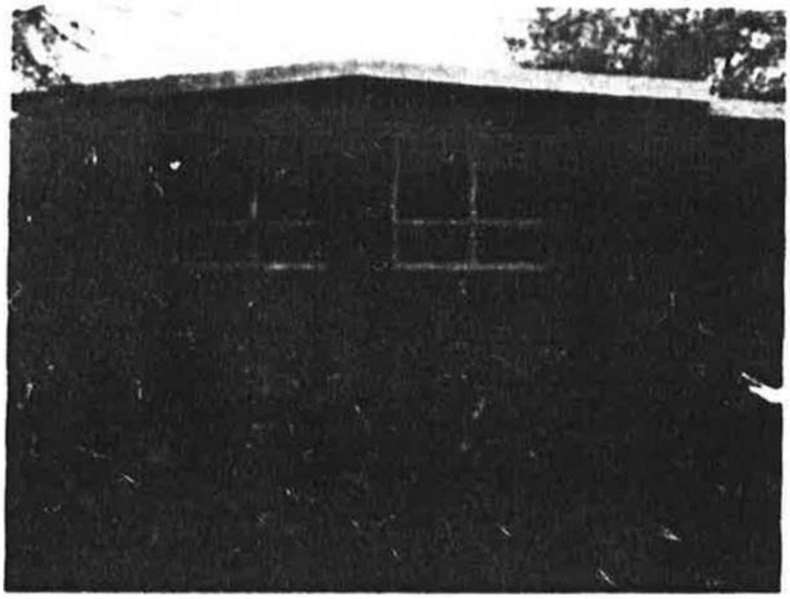


Figure 7. NORTH EXPOSURE OF IGT TEST DWELLING

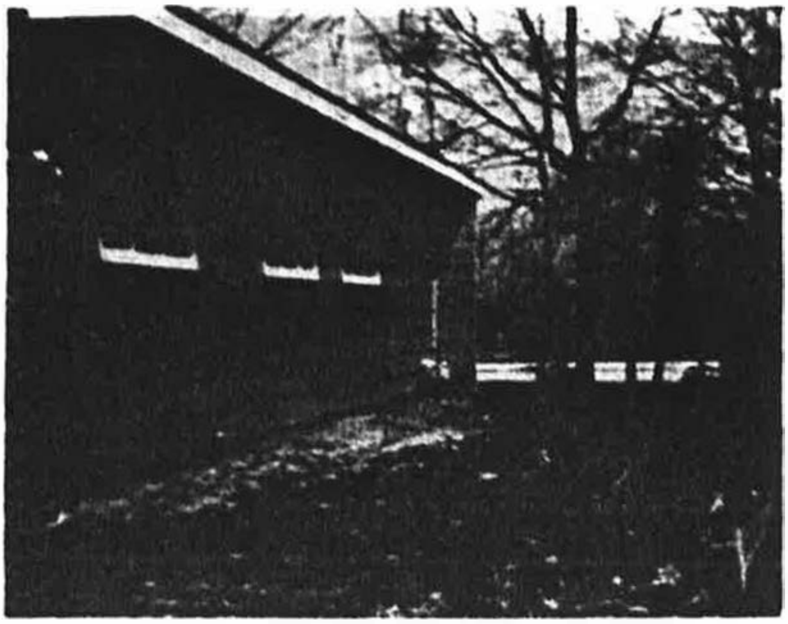


Figure 8. EAST EXPOSURE OF IGT TEST DWELLING

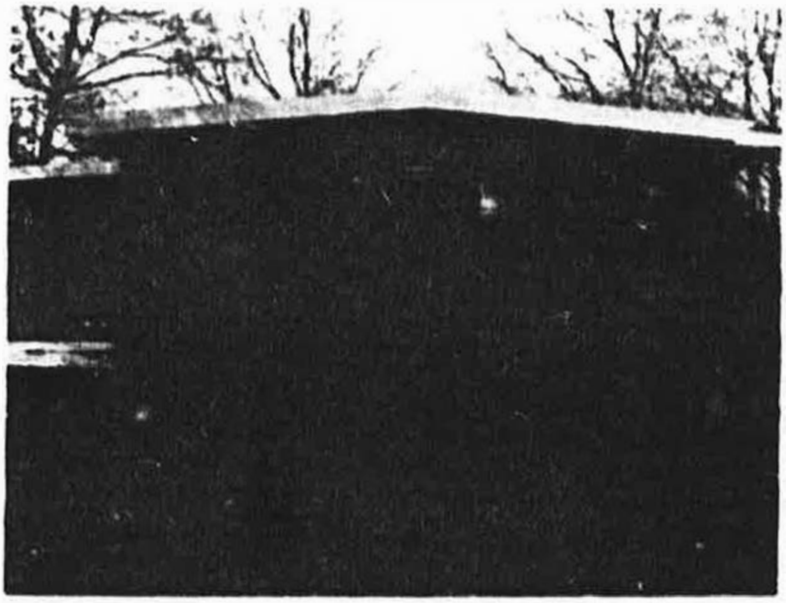


Figure 9. SOUTH EXPOSURE OF IGT TEST DWELLING

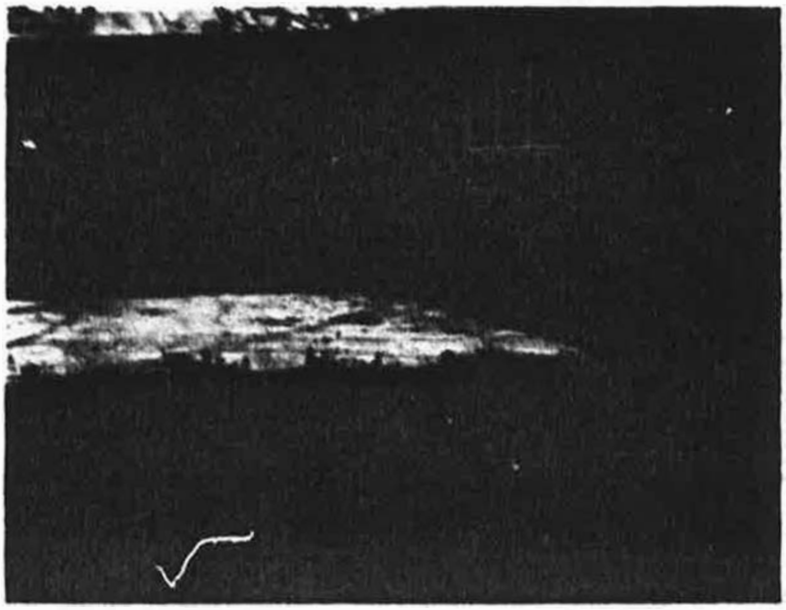


Figure 10. WEST EXPOSURE OF IGT TEST DWELLING

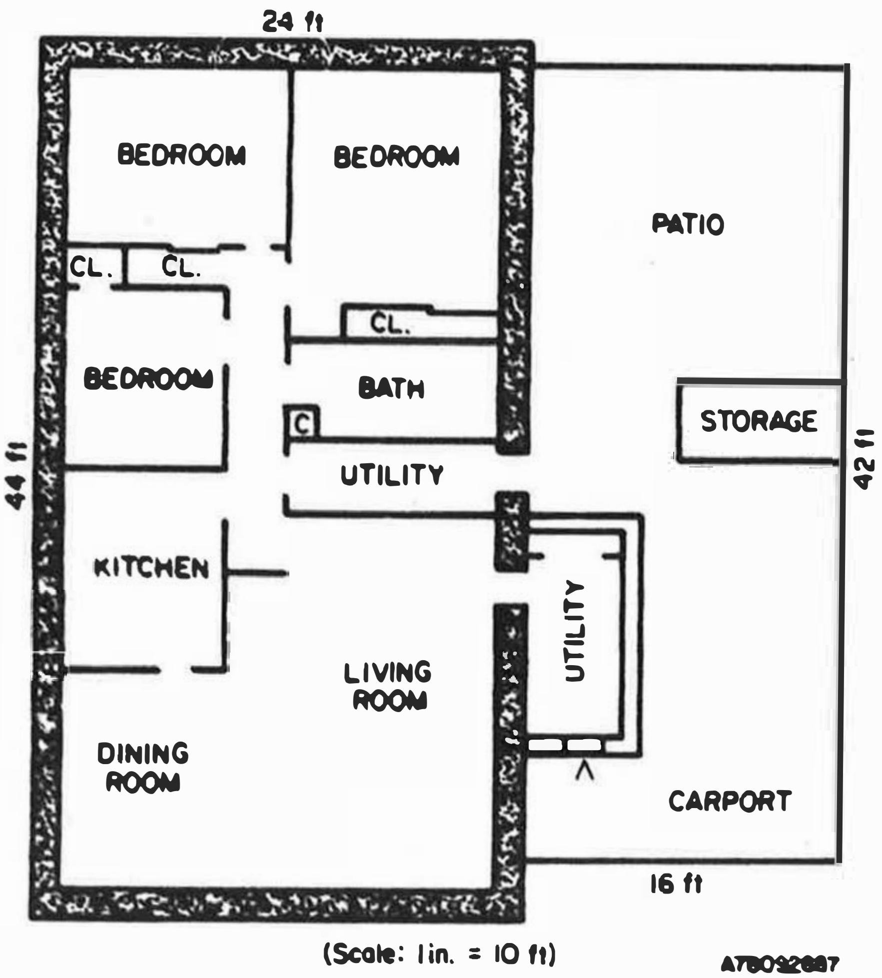


Figure 11. FLOOR PLAN OF IGT TEST DWELLING
(Scale: 1 in. = 10 ft)

utility room houses a Lawson glass-lined, 40-gallon gas water heater, an Aires 105,000 Btu/hr forced air furnace, and electric hookups for washer and dryer appliances. The remainder of the dwelling basically has painted drywalls and ceilings. The property has basically level topography with some east or west tree cover, as shown in Figure 12.

The dwelling has a carport, which is large enough for one car and has a storage area measuring approximately 4.0 by 8.5 feet. To the rear of the carport is a 16- by 18-foot patio, which was installed by the current owner within the last 2 years. At the time of inspection, the interior of the dwelling was considered to be in good condition, while the exterior was considered to be in somewhat poorer condition with repainting needed within the next 2 years. Windows throughout the dwelling are the two-glass-pane Andersen type units with screens being present on most of the opening units. The dwelling does not have additional storm windows (that is, in addition to the Andersen windows).

During a series of exploratory runs aimed at characterizing the dwelling in terms of available infiltration and exfiltration paths, it became apparent that several corrective measures were needed to ensure that any transient occurances due to dwelling decay of failure would cause no interaction with infiltration experiments. The most significant corrective actions taken were the repair of a gas line leak in the dwelling basement area, sealing of partially rotted sofit boards, and replacement of the screening of basement vents.

Additional dwelling parameters are presented in Figures 13 to 16. These four figures indicate the frame, window, and door crack lengths and positions with respect to the respective wall. Table 1 summarizes additional dwelling data, such as dwelling areas and volumes.

The two additional single-family dwellings are both two-story structures equipped with forced-air, gas-fired furnaces and are meant to provide information on the effect of house buoyance (due to height) on air infiltration. One of the homes provides full communication between the furnace room and the rest of the house, while the other allows only minimal interaction because of the furnace location. Both of these attributes contribute to house air infiltration differently and represent the two most significant variations

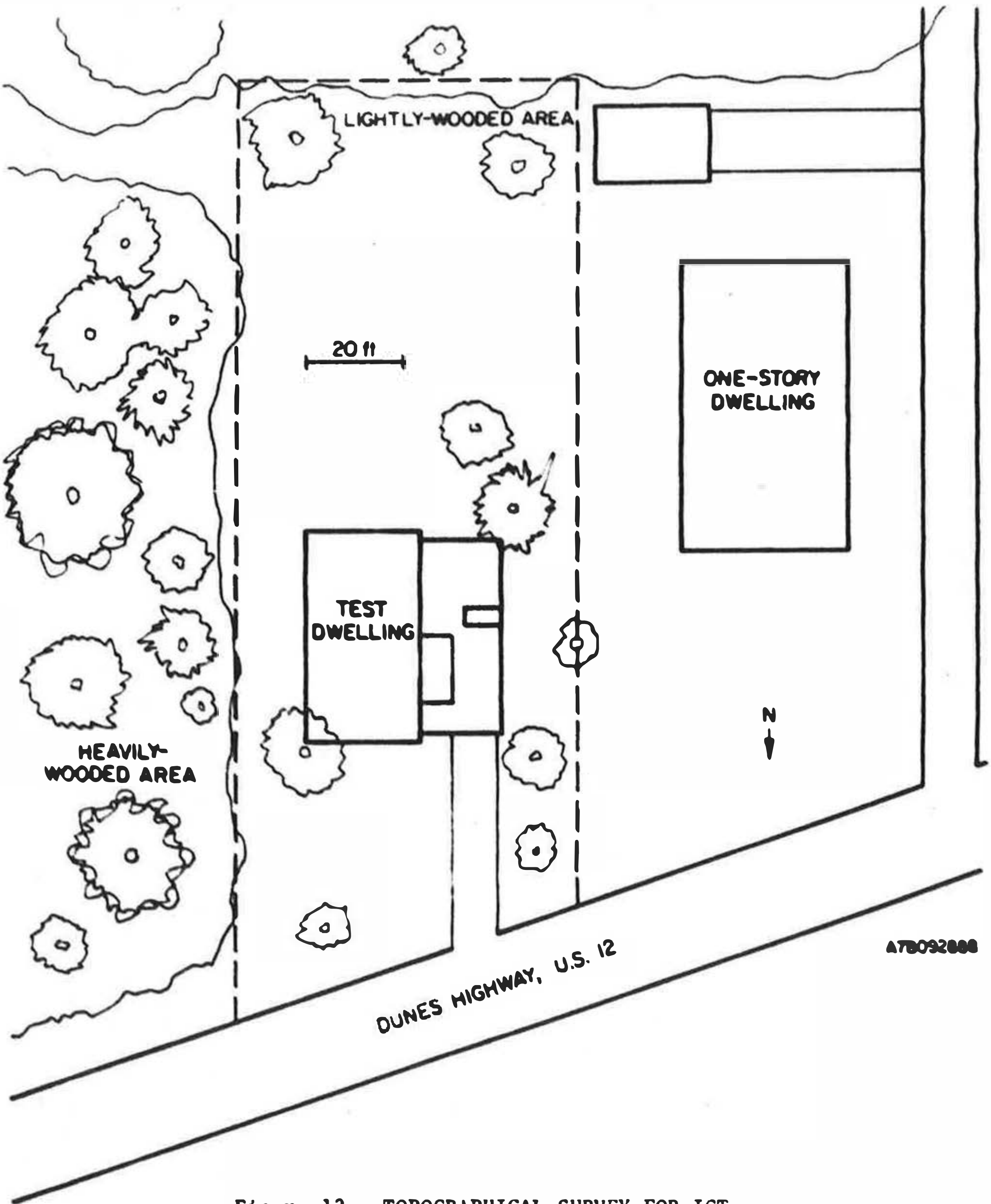
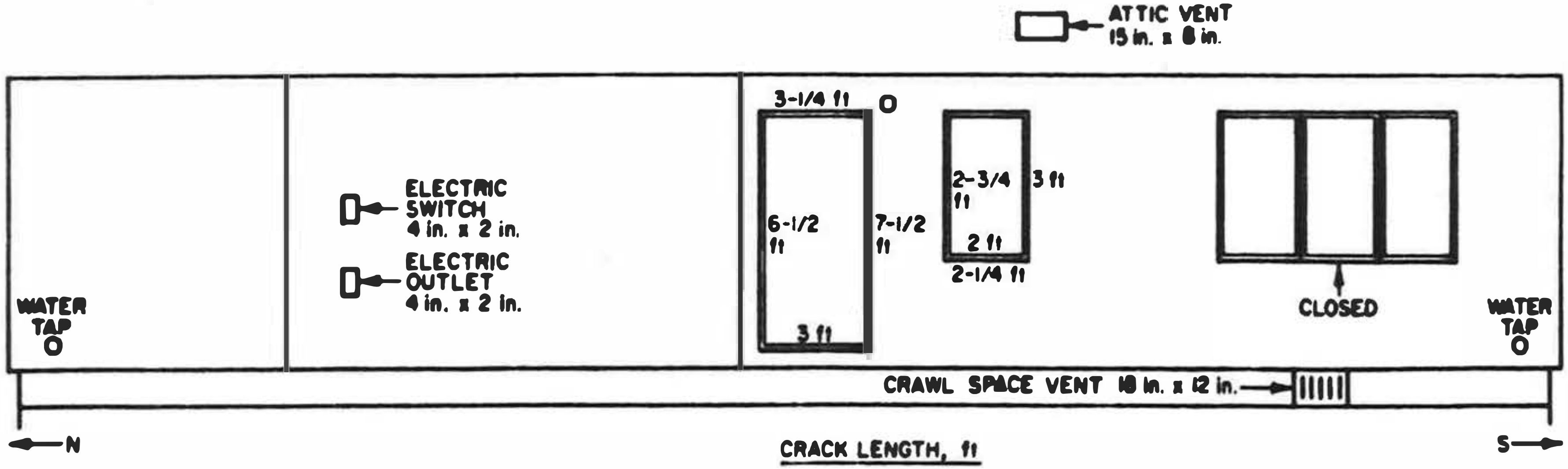
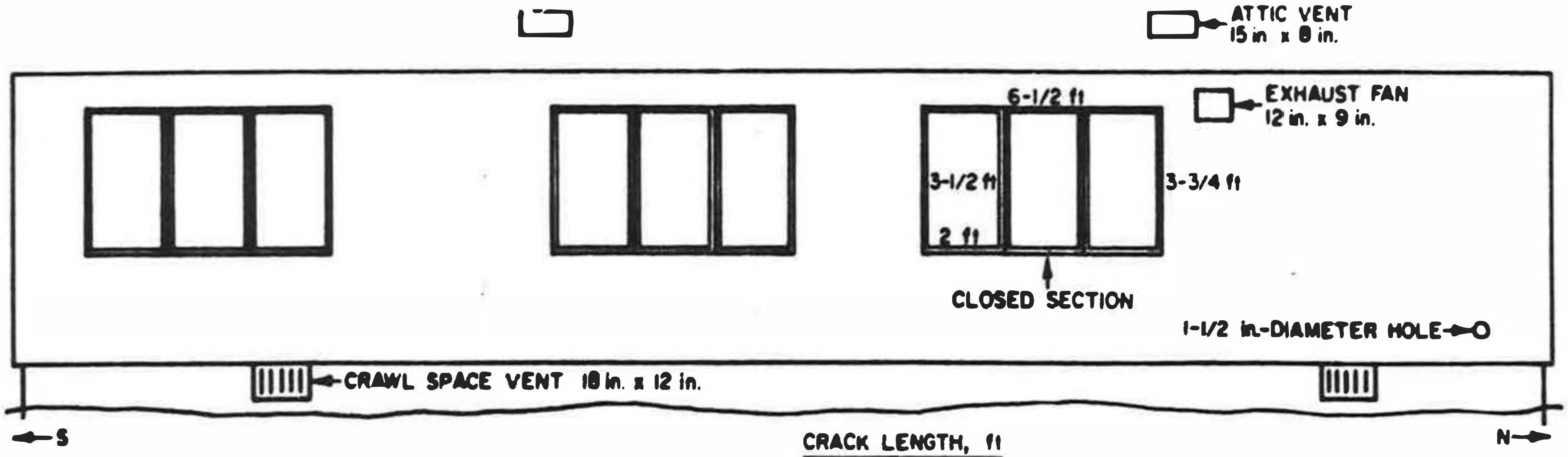


Figure 12. TOPOGRAPHICAL SURVEY FOR IGT SINGLE-STORY, SINGLE-FAMILY DWELLING (Scale: 1 in. = 20 ft)



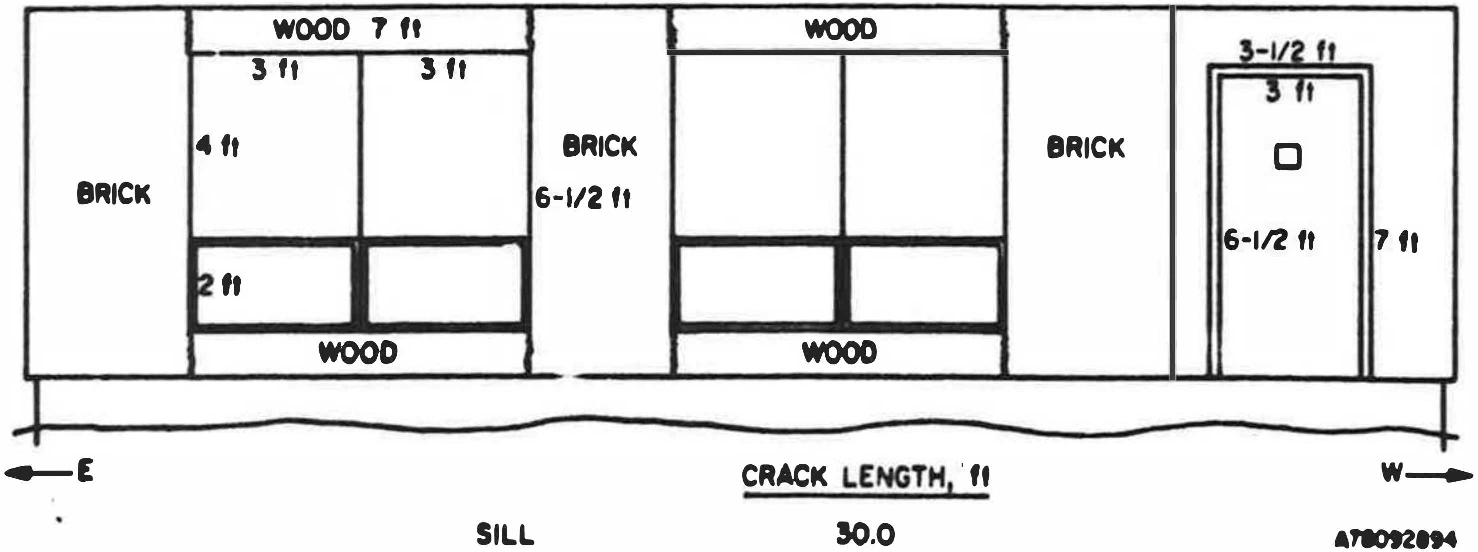
	CRACK LENGTH, ft
SILL	44.0
DOOR FRAME	21.5
DOOR	19.0
WINDOW FRAME	31.0
OPEN WINDOW	20.5
CLOSED WINDOW	11.0
MISCELLANEOUS	2.0

Figure 13. CRACK INVENTORY FOR WEST EXPOSURE



	CRACK LENGTH, ft
SILL	44.0
DOOR FRAME	--
DOOR	--
WINDOW FRAME	61.5
OPEN WINDOW	66.0
CLOSED WINDOW	33.0
MISCELLANEOUS	3.5

Figure 14. CRACK INVENTORY FOR EAST EXPOSURE



	CRACK LENGTH, ft
SILL	30.0
DOOR FRAME	21.0
DOOR	19.0
WINDOW FRAME	54.0
OPEN WINDOW	40.0
CLOSED WINDOW	56.0

Figure 15. CRACK INVENTORY FOR NORTH EXPOSURE

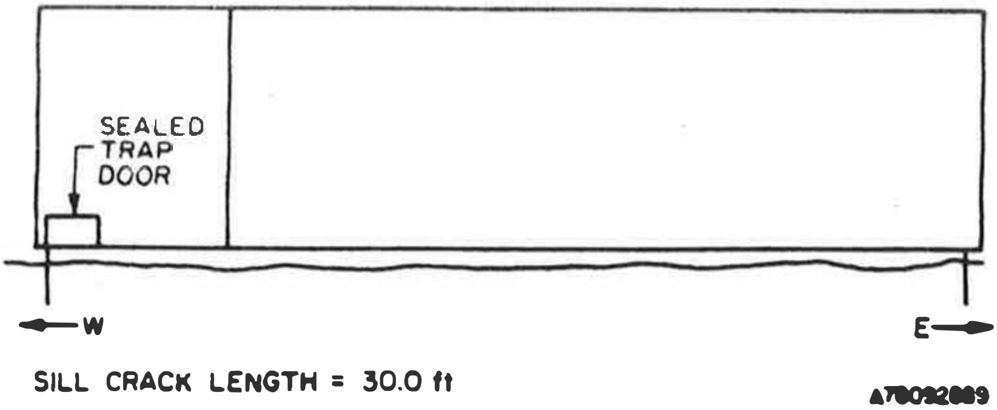


Figure 16. CRACK INVENTORY FOR SOUTH EXPOSURE

Table 1. DWELLING DATA SUMMARY

Crack-Length Summary	Feet
Total Sill Crack Length	148.0
Door Frame Crack Length	42.5
Door Crack Length	38.0
Window-Frame Crack Length	146.5
Open-Window Crack Length	126.5
Closed-Window Crack Length	100.0
Misc Crack Length	5.5
Total	607.0
Other Dwelling Parameters	**$Feet^2$**
Area of First-Floor Space	1128
Area of Basement (Crawl) Space	1056
	$Feet^3$
Volume of First-Floor Space	9024
Volume of Basement (Crawl) Space	4224
Volume of Attic Space	2184

in home construction controlling the effect of furnace operation on house air infiltration.

b. Instrumentation and Test Procedure

The instrumentation package, as summarized in Table 2 and discussed below, is designed to provide continuous, real-time measurements of the following events affecting air infiltration:

- Indoor-outdoor static pressure differential as a function of height in the house
- Dynamic pressure differential across each of the four walls at three levels in the house
- House air infiltration
- Excess infiltration (or a factor)
- Onsite weather data, such as wind speed and direction
- Indoor-outdoor temperature
- Incident furnace cycling rates.

Based on past experience and several shakedown procedures, the following procedure and schedule is utilized to obtain the needed information:

- Set up dwelling conditions according to test schedule
- Calibrate weather station for accuracy and begin data recording
- Calibrate hydrocarbon analyzers 1 and 2, determine background level, and begin data recording
- Turn furnace blower on
- Turn basement and living space floor fans on
- Inject tracer gas (ethane) into furnace duct system for 15 minutes
- Operate furnace and floor fans for an additional 15 minutes to ensure proper mixing
- Turn off living-space floor fan
- Initiate furnace operation per test schedule
- Operate basement floor fan per test schedule
- Recheck all recording units for proper operation
- Check the weather data with U.S. Coast Guard Station
- Calibrate MKS Baratron unit and begin data recording of in/out pressure
- Make wall pressure survey, if required
- Terminate run and file data sheets for processing.

Accurate pressure differential measurements along with cocurrent wind conditions of the dwelling are extremely important because they are one of

Table 2. INSTRUMENTATION OF THE ONE-STORY DWELLING

Type of Measurement	Primary Package	Range of Accuracy	Secondary Package
Indoor/Outdoor Static Pressure Differential	MKS Baratron Pressure Meter +10mm Hg Head	± 0.001-in. H_2O	None
Dynamic Pressure Differential	MKS Baratron Pressure Meter +10mm Hg Head	± 0.001-in. H_2O	None
Total House Air Infiltration	Beckman Model 400 HC Analyzer, Unit 1	± 1% Full Scale After 8 hr.	Unit 2
Excess Infiltration or φ Factor	Beckman Model 400 HC Analyzer, Unit 2	± 1% Full Scale After 8 hr.	Unit 1
Onsite Weather Data	Climet Wind Recording System C126	Speed ± 2% Full Scale Direction ± 5%	U.S. Coast Guard Station @ Michigan City, Indiana
Indoor/Outdoor Temperatures	Multigauged Type J Thermocouples	< ± 1%	Hg-Filled Glass Thermometers
Furnace Cycling Rates	Single Type J Thermocouples with Recorder	None Required	Visual Count

the ways to validate the infiltration model. Because the ΔP's across the walls of the dwelling are of the magnitude of 0.01 inch of water column, a highly sensitive instrument is required. The instrument currently being used to measure these pressure drops is an MKS Baratron electronic pressure differential sensor, capable of recording pressure drops of 0.001 inch of water column.

The indoor-outdoor static pressure differential is directly measured by connecting a static pressure probe located some distance from the dwelling — referred to as the remote pressure probe — to one end of the pressure differential sensor and the other static pressure probe located indoors, to the other end of the sensor (See Figure 17.) The dynamic pressure differentials measured through the wall are recorded using the same instrument and procedures as mentioned above. The only major difference is the placement of the outdoor probe, which in this case extends about 1/4 inch beyond the exterior siding. (See Figure 18.) A typical time trace obtained by the direct method is shown in Figure 19.

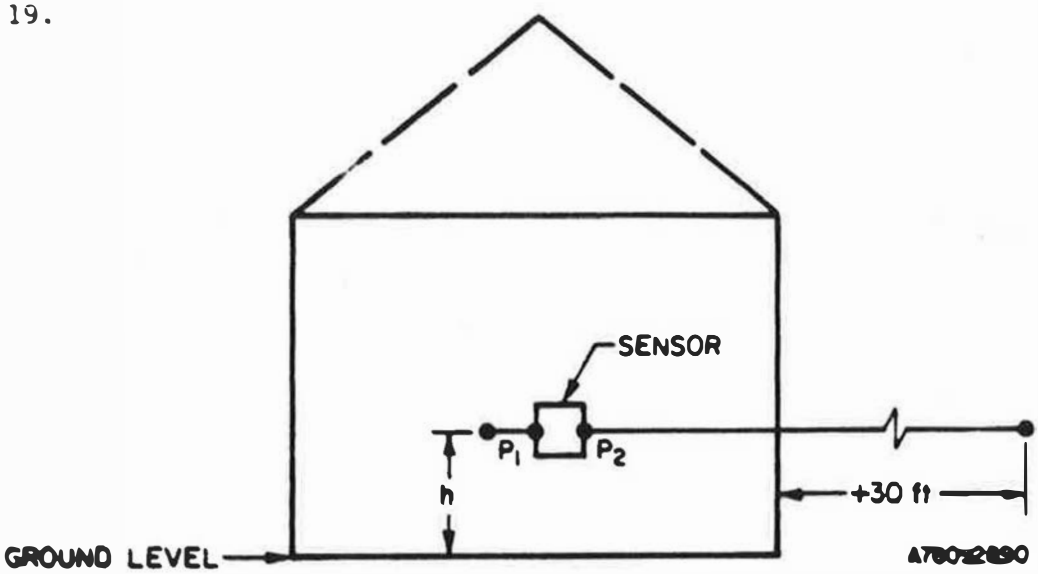


Figure 17. STATIC DIRECT MEASUREMENT OF ΔP WITH INDOOR/OUTDOOR PROBE PLACEMENT

House infiltration rates are measured by following the declining tracer concentration with time — in this case ethane — after injection to about 400 ppm into the dwelling. Historically, ethane has been used as the tracer gas for all IGT infiltration studies, because its density is almost identical to that for air and it is non-toxic. The measurement is obtained with a Beckman Model 400 Hydrocarbon flame ionization analyzer that continuously monitors the

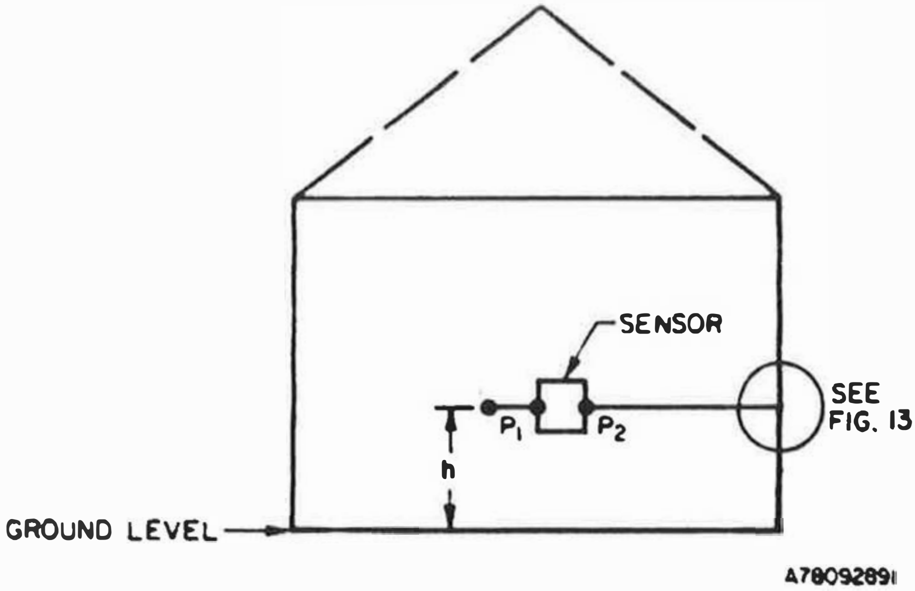


Figure 18. DYNAMIC DIRECT MEASUREMENT OF ΔP
THROUGH-THE-WALL PROBLEM PLACEMENT

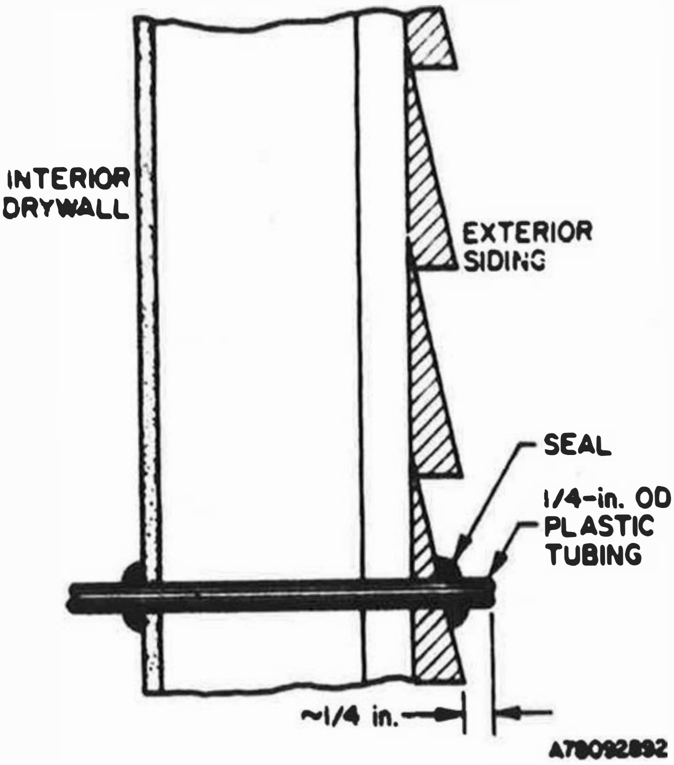


Figure 19. DETAIL OF PROBE PLACEMENT THROUGH THE WALL

ethane concentration in the dwelling air sample stream. The input signal from the analyzer is recorded and the data are then plotted versus time on semilog paper to give the house air infiltration rate in air changes per hour during the selected time period. A typical time trace is shown in Figure 20.

Excess infiltration (or φ-factor) data are measured using the same instrumentation. However, a slight procedure modification is applied so that this measurement can be carried out in conjunction with the house air infiltration measurement. When only excess infiltration is required, a constant flow of ethane is injected into the furnace draft diverter-chimney entry, and the resultant tracer concentration is measured at the chimney exit. The decrease in ethane concentration, due to dilution air past the diverter, is then used to calculate and report the chimney flow or excess infiltration.

On the other hand, when such a measurement is to be made concurrently with the measurement of house-air infiltration rate, care should be exercised so that the changing house tracer concentration will not interfere with the measurement of φ-value. To guard against this problem, the following revised procedure is used. A sample probe is placed at the furnace vent pipe/chimney entrance to monitor tracer gas inlet levels, and a sample probe is placed 1 foot below the chimney exit to monitor tracer gas exit levels. Slightly downstream from the inlet sample probe is the tracer injection tap. By using a timed three-way selenoid system, background or inlet and exit trace gas levels can be monitored continuosly, with the difference indicating the stack flow, even though both traces are continuously changing. Figure 21 presents a simplified schematic for carrying out these simultaneous measurements and Figure 22 presents a typical time trace of house air infiltration determination.

The magnitude of house air infiltration, as well as pressure differences, is greatly affected by wind speed and direction. To accurately monitor these meteorological variables, a Climet Wind Recording System is installed about 30 feet above ground level (14 feet about the peak roof line). This system is capable of measuring wind speeds of up to 100 mph with a threshold of 1.25 mph and an accuracy of $\pm 2\%$. The wind-direction sensor has a threshold of 1 mph and an overall accuracy of $\pm 5\%$ from 0 to 359 degrees. A typical wind speed/direction trace is shown in Figure 23.

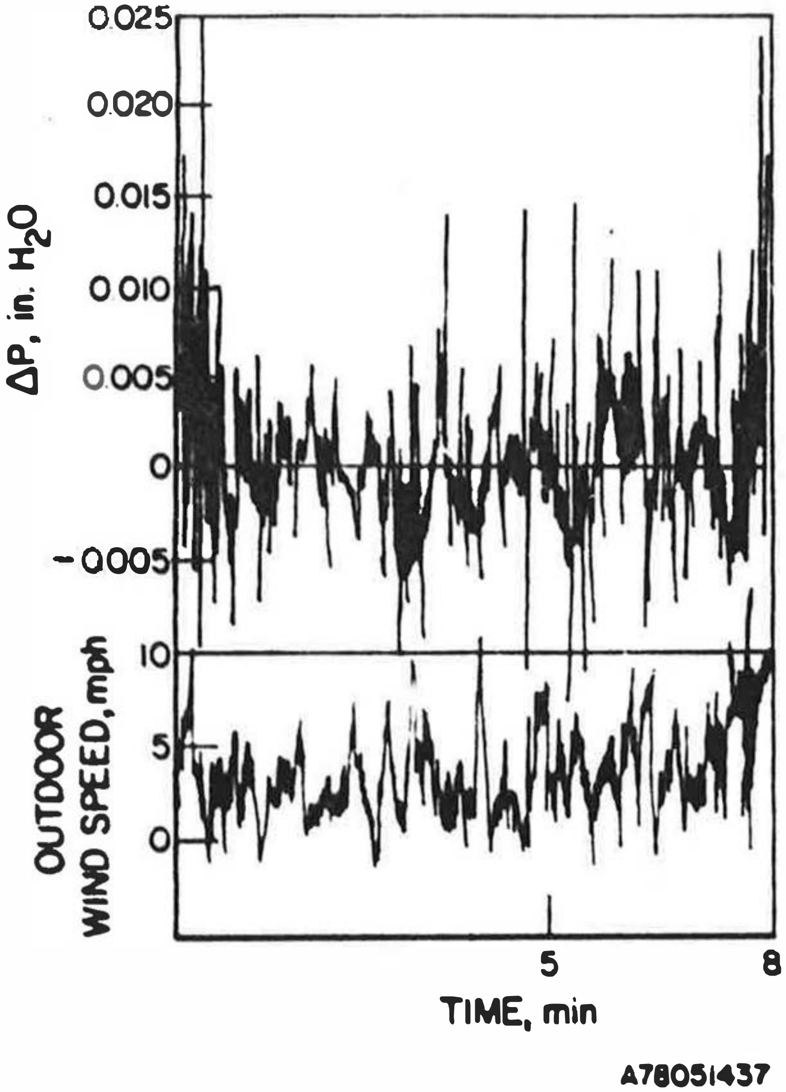


Figure 20. TYPICAL TIME TRACE OF PRESSURE DIFFERENTIAL MEASUREMENT

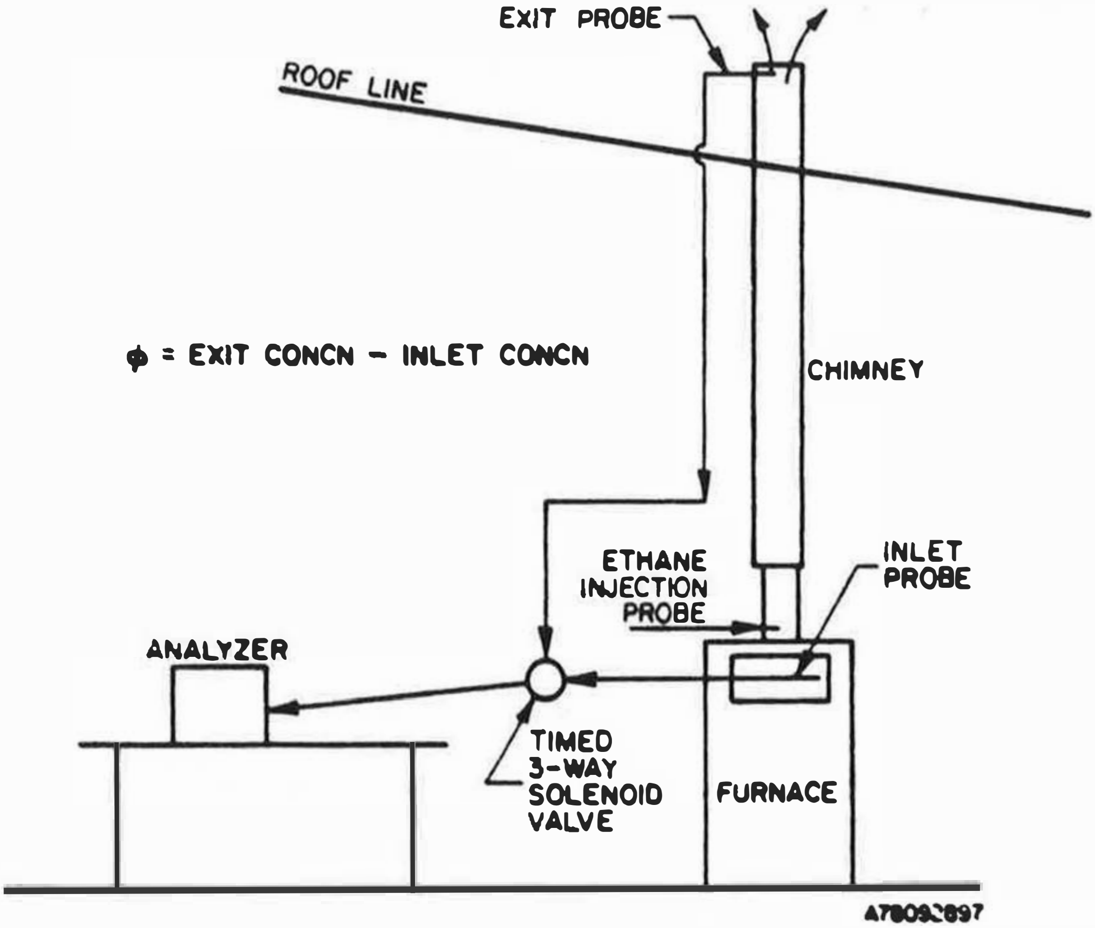


Figure 21. PROBE ARRANGEMENT FOR DETERMINING EXCESS INFILTRATION (Φ-FACTOR)

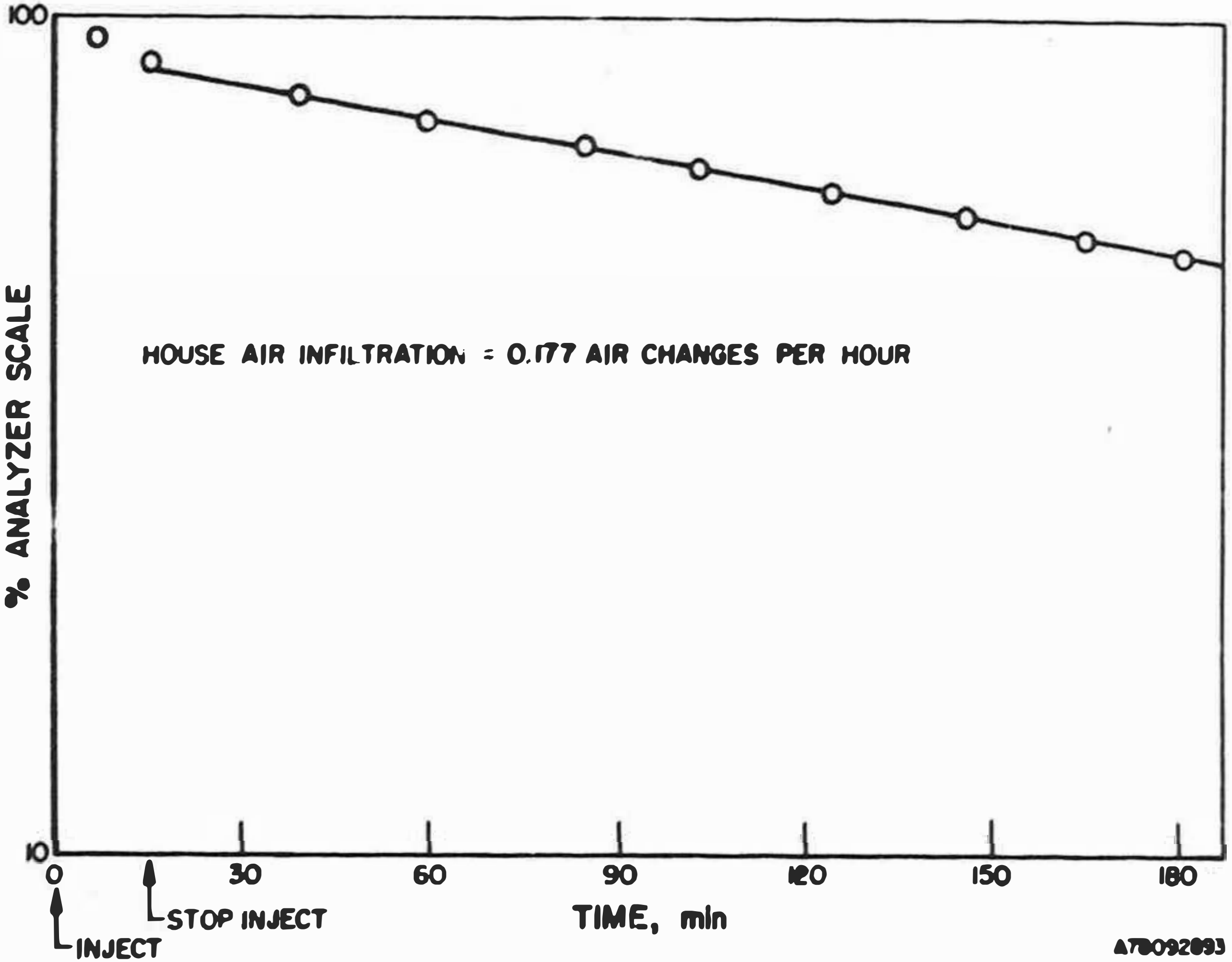


Figure 22. TYPICAL TIME TRACE OF HOUSE AIR INFILTRATION

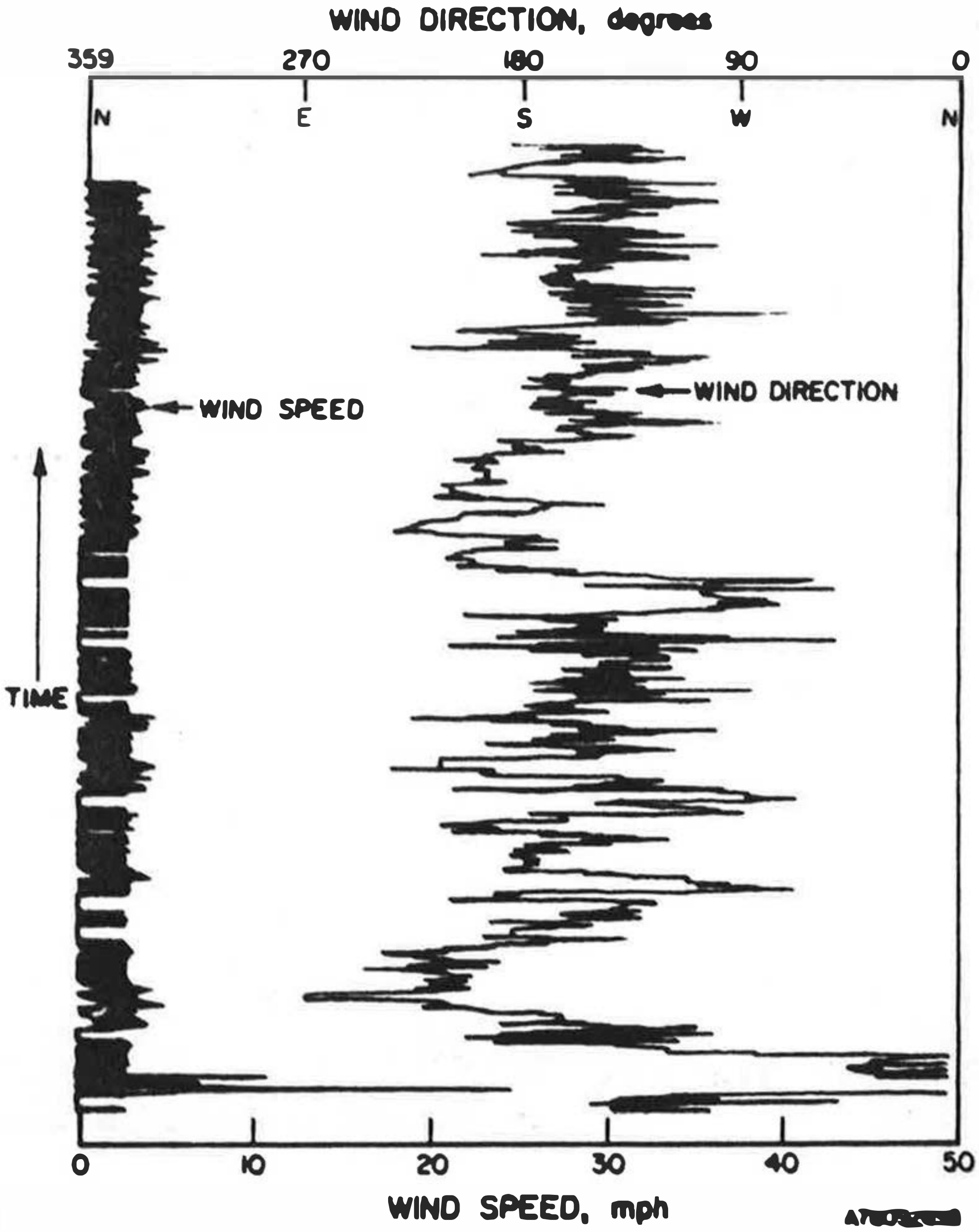


Figure 23. TYPICAL SIMULTANEOUS WIND-SPEED AND WIND-DIRECTION TIME TRACES

Temperature measurements of interest are monitored with a 12-channel recorder. Using Type-J thermocouples referenced to 32°F, we monitor indoor, outdoor, basement, and attic dwelling temperatures and furnace flue (one thermocouple for each section) and furnace vent temperatures, both inlet and exit. Additional temperature capabilities, such as one or more register temperatures, can be monitored if required. Furnace operation is also monitored separately, using a Type-J thermocouple in one of its sections. Upon ignition, the change in temperature is recorded on a single pen recorder with instant response; this is very useful for indicating cycling furnace performance during the winter tests.

c. Experimental Results

The experimental work covered the following:

- Equipment shakedown and calibration
- Exploratory runs to determine the effect of house and weather parameters on infiltration and indoor-outdoor static pressure difference, effect of reference probe placement, and the participation of the crawl space and attic in the overall infiltration dynamics of the house
- Determination of the infiltration characteristics of the house under no-driving-force conditions
- Characterization of the window and door leakage characteristics from ASHRAE data.

The experimental data collected correspond to conditions during which very little variation in wind speed and indoor-outdoor temperature differences were observed. The actual data are summarized in Table 3.

Effect of the Furnace Blower on House Pressure and Infiltration

Table 3 shows that under very low driving force conditions the infiltration rates in the house ranged from 0.19 to 0.26 air changes per hour, with an average of 0.22 ± 0.02 air changes per hour with the furnace blower on. At the same time, it was noted that a slight negative pressure existed in the house and that a significant tracer concentration built up rapidly in the crawl space and sometimes in the attic as well. With the blower off, on the other hand, it was found that the indoor-outdoor static pressure

Table 3. BASE-LINE DATA FROM THE SINGLE-STORY TEST HOME

Run No.	Dwelling Condition	Time of Test, min.	Avg Wind Conditions Speed, mph	Direction	Avg Temperatures In	Out	Time Of Day, 24 hours	Infiltration Rates, air changes/hr Living	Attic	Basement
1	As Is Blower On	270	9	S	78	78	10-14.5	0.24	--	--
5		435	<5	NW	73	68	9-16.25	0.19	--	--
7a		300	5	S-SW	81	80	15-21	0.20	--	--
7b		390	Calm	--	72	72	21- 3.5	0.24	--	--
7c		150	2	S-SE	71	68	3.5-6	0.21	--	--
8		420	3	N	76	76	10-17	0.21	--	--
12		420	4	SE	67	71	16-23	0.20	--	--
13a		180	3	S-SE	68	75	9-12	0.26	--	--
13c		105	Calm	W-NW	70	82	13.5-15.25	0.25	--	--
13e		140	2	N-NW	73	72	17-21.5	0.21	--	--
15a		165	2	N-NW	67	73	8-10.75	0.23	--	--
11	As Is Blower Off	420	<3	N-NW	72	67	16-23	0.19	0.46	1.37
13b		90	3	W-SW	70	80	12-13.5	0.08	--	1.00
13d		105	2	N-NW	72	82	15.25-17	0.07	--	--
14		420	Calm	S	71	69	21-4	0.18	0.24	1.08
15b		90	3	N-NW	75	75	10.75-12.25	0.07	--	1.32
2*	Electrical Outlets Sealed, Blower On	240	5	N-NW	78	80	9-13	0.26	--	--
6	Electrical Outlets Sealed, Blower On	420	3	W	65	67	9-16	0.22	--	--
3	Attic/Basement Vents Sealed, Blower On	345	<5	SW	70	72	9-14.75	0.16	--	--
4	Attic/Basement Vents and Electrical Outlets Sealed, Blower On	360	4	NW	60	65	9-15	0.19	--	--
15c	Furnace Vent Blocked, Blower Off	105	3	N-NW	74	77	12.25-13.75	0.09	--	--
15e	Stack Blocked, Blower On	450	Calm	N	70	79	14.75-22.25	0.12	--	--
15f	Stack Blocked, Blower Off	240	Calm	N	70	66	22.25-2.25	0.17	0.38	0.99

*Gas Leak In Dwelling Interferred With Tracer Gas Concentration.

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difference increased to about zero under calm wind conditions (or a slight positive pressure with wind), and the infiltration rate decreased to about 0.07 air changes per hour in the living space.

With the furnace blower on the infiltration rate in the crawl space was measured, on fire occasions, to be 1.0 air changes per hour or greater. It is obvious that such a high air change rate can be due to duct losses to the crawl space due to blower induced pressure drops.

Infiltration Into the Attic

The increase of tracer concentration in the attic with the blower on always lagged significantly behind the increase in the crawl space. This suggests that the leakage is from the crawl space to the attic rather than from the living space directly to the attic, and this is also consistent with the fact the the living space infiltration rates, with the electrical outlets sealed, were the same (0.22 to 0.26) as when unsealed (0.19 to 0.26).

We also observed that the leakage of tracer gas to the attic was quite sporadic and could occur either with the blower on or off. In each case, it appeared to be associated with a small indoor-outdoor temperature difference (ΔT = 1° to 10°F). It occurred with either positive or negative ΔT, but never at zero ΔT. This suggests a convective transfer through the wall stud spaces, which could occur by different mechanisms:

- Regular stack action because of pressure differentials between top and bottom of house, generated by indoor-outdoor ΔT
- Convective transfer within each stud space because one side of the space is cold and the other side is warm
- Stack action in one wall (south) generated by solar heating.

As indicated above, the infiltration of tracer gas into the attic was, most of the time, from the crawl space, while operating with the furnace blower on. However, at least on one occasion, air filtration into the attic came from the living space, when we operated with the furnace blower off. This transport was presumably through the electrical outlets in the walls, powered by conventive (buoyancy) forces.

Contribution of Open Chimney to Infiltration

We earlier discussed that, under no wind or ΔT driving force conditions, the maximum air infiltration rate in the living space of the test home with the furnace blower on was found to be 0.26 air changes per hour, with the chimney open. Under identical conditions, but with the chimney closed, the air exchange rate measured was 0.12 air changes per hour. These numbers would suggest that a significant portion of the infiltrated air under these conditions must be coming through the chimney. This supposition was subsequently proven by measuring the trace concentration (which has been introduced only to the living space) at the bottom of the chimney. These data also suggest that almost one-half of the total house permeability can be attributed to the open chimney $\left(\frac{0.26 - 0.12}{0.26} = 0.54\right)$.

Permeability Inventory

Operating under no driving force conditions, but with the furnace blower continuously on, we observed a negative (whole-house) average static pressure difference, ΔP_x, in the range of 0.002 to 0.003 inch of H_2O. We have used this pressure, the infiltration rates for the house with the stack open and closed, and the usual infiltration equation (equations):

$$I = K(\Delta P)^{1/2} \tag{21}$$

to compute the value of the permeability constant K for the house plus stack, the house only, and the stack only. The estimated values are —

K for house + stack = 712 CF/min per inch H_2O

K for house only = 304 CF/min per inch H_2O

K for stack only = 408 CF/min per inch H_2O

For comparison, we have also estimated the permeability of the house, under these conditions, using the measured crackage data and ASHRAE data on average crack permeability. Also, we used IGT's stack-loss model (A.G.A. Project HC-4-33, Final Report for 1976) to compute stack permeability. The results are shown below:

K for weather-stripped windows = 152 CF/min per inch H_2O

K for doors with storms = 49 CF/min per inch H_2O

K for framing and sill plate = 154 CF/min per inch H_2O