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AIR INFILTRATION MODEL FOR RESIDENCES

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INTRODUCTION

Air infiltration has long been recognized as a significant portion of the total heating or cooling loads in a residence. Infiltration rates are extremely difficult to predict accurately for a residence because of the numerous variables that are involved, the complexities of interactions among the variables and the inability to exactly determine the magnitude of the variables. In order to improve residential energy prediction procedures, a detailed investigation was conducted by Ohio State University under EPRI sponsorship to obtain measured data at nine research residences in Columbus.

The objective of this investigation was to develop a generalized computer simulation model to predict hourly air infiltration rates into a residence. The model should account for the suspected parameters that influence air infiltration, such as weather, orientation, crack sizes, combustion processes, exhaust fan operation, and window and door openings.

BACKGROUND

Most previous work has modeled infiltration using the following general form which has been reported in several articles: (1-16)

$$AI = A + B \times \Delta T + C \times WS$$

Where:

AI = Hourly air infiltration

A,B,C = Statistical linear regression constants for a particular residence

ΔT = Indoor-outdoor temperature difference

WS = Wind speed

Typically, each report was the result of research conducted in 1-24 homes and the data collected in each was not extensive. The usual procedure involved in these investigations was to measure air infiltration by means of a tracer gas. Simultaneously, weather parameters were measured and the results presented in the form of linear equations or statistical regressions. The significant points of each report are presented in the full documentation report to the sponsor. No substantial consistency among the various results was found except for the intercept at about 0.1 air changes per hour.

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No mechanism was identified which would account for this infiltration in the absence of driving forces.

DATA COLLECTION

The basic approach taken in the measurement of air infiltration was to use the tracer gas technique. Justification of this approach was based on two arguments. First, the tracer gas technique does not interfere with the natural air infiltration process. This is a significant advantage over the exhaust fan approach which requires a fixed, indoor-outdoor pressure difference. The second advantage of the tracer gas technique was the availability of an automated device which would collect data continuously for several days at a time before manual adjustments were required.

The device used on this project was constructed by Dr. David T. Harrje of Princeton University. The device was manually fabricated from components and is not commercially available as a package. The design was similar to other units constructed by Dr. Harrje which were used on the Twin Rivers project. Minor improvements were incorporated into the design and fabrication of this unit based on his previous experience.

The major components (see Figure 1) of the air infiltration measuring device were:

1. Leak detector unit.

2. Removable SF_6 storage and injection unit.

3. Carrier gas, 99.995% pure argon, storage and injection components.

4. Timer control panel.

5. Sampling system.

6. Strip chart recorder.

Within the detector unit, the sampled air is separated into components of varying molecular weight. A 500 mc tritium source recognizes and records the electron absorptivity of the separated components of the sampled air. Sulfur hexafluoride concentrations are measured in the range of 5 to 65 parts per billion illustrating the sensitivity of the detector. The concentrations were permanently recorded on the strip chart recorder.

The sequential steps in a typical 3-hour cycle are:

1. Injection of 10 cc of SF_6 into the return air duct adjacent to the furnace once every three hours.

2. Sampling of return air every 15 minutes and recording results on strip chart recorder.

A comprehensive report on the instrumentation can be found in Reference 16.

A typical output of the data stored on the strip chart recorder is presented in Figure 2. The standing current, I_0, was usually between 70-90 (arbitrary units), while the SF_6 current would vary considerably depending upon the concentration levels. Each value of I and I_0 was recorded every 15 minutes. Three observations, at 30 second intervals were averaged to determine the mean value of I.

Calibration of the device was achieved by use of a zero leakage, plexiglass, 10,000 cc piston-cylinder. The calibration procedure was developed by Dr. D. T. Harrje of Princeton University.

A complete description of the test sites can be found in Reference 17; Table I summarizes the characteristics of the sites.

Air infiltration measurements were made with various heating systems, including electric baseboard, central electric furnace, heat pumps, and central gas furnace.

MODEL FORMATION

The analysis of the infiltration was divided into two categories. The first category consists of linear models which are similar in format to those presented by previous investigators. Due to the enormous quantity of data collected, it was felt that the linear models could be analyzed statistically and ultimately be generalized into a unified model applicable for any residence. The subsequent failure of this approach then led to the development of the second category. (A detailed description of the linear modeling efforts are provided in the full documentation report to the sponsor - Sections 9.5.1 and 9.5.2).

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

The primary motivations for shifting the emphasis from the linear models to physical models were to reduce the quantity of statistical regression coefficients required and to be able to generalize to other houses. Three coefficients were required in the linear models. These are always dependent on the particular house which complicates the application of that approach to a new residence. It was anticipated that the physical models would, at best, be completely deterministic from theory alone or require, at most, a single statistical regression coefficient which would be somewhat constant for all residences or at least for a particular residence style.

The development of the physical models proceeded in a progressive path beginning with the weather variables and adding the subsequent terms in a stepwise procedure until a final model was developed. The final model was determined to be complete when the influence of all of the variables had been evaluated and incorporated into the model according to their explanatory importance in predicting the measured air infiltration values.

The first variable considered in the physical model was the influence of temperature differences. The temperature difference is not a direct influence on air infiltration, but causes a pressure difference due to air density. The pressure difference is given by the following equation which is presented in the ASHRAE Handbook and Product Directory (18):

$$\Delta P_T = 0.52 \cdot P \cdot h \cdot \left(\frac{1}{T_o} - \frac{1}{T_i}\right) \qquad \left[\Delta P_T = 34 \cdot P \cdot h \cdot \left(\frac{1}{T_o} - \frac{1}{T_i}\right)\right] \qquad (2)$$

Where:

ΔP_T = Theoretical pressure difference across enclosure due to stack effect, inches of water (Pa)

P = Absolute pressure, lb/in^2 (kPa)

h = Distance from neutral zone, or effective stack height, ft. (m). For purposes of this project, the following definitions of h were utilized: Two Story, h = 8 ft. (2.4 m); Split Level, h = 6 ft. (1.8 m); and for a Ranch, h = 4 ft. (1.2 m)

T_o = Absolute temperature outside, ^oR (K)

T_i = Absolute temperature inside, ^oR (K)

The second variable is the pressure difference due to wind. The wind pressure term was calculated by using the equation presented in the ASHRAE Handbook and Product Directory (18):

$$\Delta P_W = \frac{0.2549}{T_o} \cdot Vel^2 \qquad \left[\Delta P_W = \frac{176.5}{T_o} \cdot Vel^2\right] \qquad (3)$$

Where:

P_W = Theoretical pressure difference across enclosure due to wind effect, inches of water (Pa)

Vel = Wind speed, miles per hour (m/s)

Associated with the normal velocity component on each exposure is a characteristic opening or crackage related to the windows, doors, wall areas, and sills. The procedure employed to calculate the equivalent crack lengths was adopted from the crack method presented in the ASHRAE Handbook and Product Directory (18). The length of each crack was multiplied by the appropriate air infiltration factor and the sum was divided by the factor for non-weather stripped, average fit, double hung, wood windows. Thus, the equivalent crack lengths can be compared directly to determine the relative differences between exposures.

Seven different physical models incorporating pressure differences, wind direction, and exposure relative equivalent crack lengths were used. Each of these took the form:

$$INFP = \beta_o (A)$$

$$A = f(C_i, \Delta P_i)$$

Where:

β_o = Statistical regression constant

$C_{F,B,L,R}$ = Equivalent crack lengths on the Front, Back, Left, and Right surfaces of the structure

ΔP_i = Theoretical pressure difference across Front, Back, Left and Right surfaces of the structure

i = Index for surface, Front, Back, Left, Right

The wind direction concept was developed into the above equation by defining the velocity term to be the normal component to a particular surface. Thus, the average wind direction can only be normal to a maximum of two adjacent surfaces during the hour.

In each of these models, a consistency was sought in β_o among several houses and several time periods for the same house, but not found, thus becoming the impetus for the succeeding model.

The failure of these models, which included wind directional effects, was the motivation to drop the directional concept. The results indicated that the air infiltration could not be analyzed by considering wind directional components as originally thought, but that air infiltration occurs in a more general pattern which can be characterized in simpler models. The simplest and most successful physical model was:

$$INFP12 = \beta_o C_T \left(A \Delta P_T + B \Delta P_W\right)^{1/2} \qquad (5)$$

Where:

INFP12 = Infiltration

C_T = Total equivalent crack length

A,B = Relative weights

For wind forces, the range of A for inflow pressure is from 1 to $\sqrt{2}$, i.e., at a minimum broadside to one side, and is a maximum forty-five degrees to two sides. The thermal pressure acts upon four sides, but the use of 1/2 total height (Eq. 2) to calculate that term reflects the pressure difference at the bottom of the conditional space. The average pressure is one-half that value. The choice of a pressure used, of course, depends on the location on the in and exfiltration. Several trial analyses led to relating the wind and thermal effects in proportion of their maximum values, letting A equal 4, and B equal $\sqrt{2}$.

Additions of terms to account for door openings, exhaust fan operation a drift in measured data improved the correlation with measured data but increased the complexity of the model inordinately and reduced generality.

ANALYSIS OF DATA

The usable data set consisted of over seven thousand observations of tracer gas concentrations at six different houses and three apartments. The range of measured data is shown in Figure 3. The data set was reduced by integrating the fifteen minute measurements into almost two thousand hourly observations. The model of Equation 5 was used with results presented in Table 2. The variation in β_o could be construed as a measure of quality of workmanship as well as being due to unaccounted for parameters. No reasons could be determined for the exceptionally high value for site HTSG. Site PAEG is an end unit apartment having three exposed surfaces vs. the two for sites KAMG and OAMG. Since the procedure weights only crack length, this could indicate significant infiltration through other paths. A more graphic illustration of the success of this model is given in Figures 4 through 7 which illustrate measured vs. calculated results.

PRESENCE OF CHIMNEY

Several investigators, notably the Institute of Gas Technology, have attempted to quantify the increase in infiltration due to presence of a fossil fuel heating system with its attendant chimney. In Reference 19, they estimate this effect as adding 30 to 45 cfm (14 to 21 l/s) to infiltration. In Reference 8, Elkins reports on tests of identical homes indicating this effect adds an average 74% to infiltration. In this project, no difference was expected since the heating equipment (and chimney opening) was in the basement, without air flow connection to the duct system. Analysis of the two sites with changed heating systems revealed, however, that additional exfiltration to the basement from the living area was caused by the presence of the chimney. Results are presented in Table 3. An average 12-1/2% increase was identified.

CONCLUSIONS AND RECOMMENDATIONS

For the purposes of estimating hourly air infiltration in residences for energy calculation, the algorithm in Figure 8 is suggested. The values of CSTAT were calculated as the means of β_o for houses (apartments excluded), with chimney effects as identified above.

The data acquisition procedure could be improved by developing a procedure to replace the strip chart recorder to expedite the data reduction procedure. A more significant improvement would be to incorporate the capability of increasing the sampling rate of the device. This would allow for a more detailed investigation of the short duration effects, such as door openings and exhaust fan operation.

From an analysis viewpoint, improvements could be realized if the air infiltration measurements were supplemented with simultaneous measurements of exterior and interior pressure differences and distributions, boundary layer wind effects, and interior air flow paths. These measurements should be on a time basis significantly shorter than the hourly intervals utilized on this project to determine whether the flow is steady-state or is characterized by pulsations and eddy flow.

The existing data set is far from fully exploited. The data are available on magnetic tape from EPRI to any researcher who desires to pursue the subject.

Implementation of these recommendations would provide the researcher with the supporting data to analyze the assumptions made on this project and could suggest the inclusion of additional terms or interactions which would improve the model.

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TABLE I

TEST SITE DESCRIPTION

SITE	NO. OF OCCUPANTS	HOUSE STYLE	VOLUME(ft^3)*	ORIENTATION	HEATING SYSTEM
KTSC	4	2-Story Frame	12818	N12°E	3 Different Types
ETSC	4	2-Story Frame	12818	N24°E	3 Different Types
HSLG	4	Split Level	12305	S25°W	Forced Air Gas Furnace
CTSE	0	2-Story Frame	12818	N 7°E	Forced Air Electric
KAWG	4	Townhouse Apt.	6273	N 5°E	Forced Air Gas Furnace
OAMG	2	Townhouse Apt.	6273	N 5°E	Forced Air Gas Furnace
PAEG	2	Townhouse Apt.	6273	N 5°E	Forced Air Gas Furnace
HTSG	4	2-Story Frame	12818	N32°W	Forced Air Gas Furnace
SRSG	4	Ranch	14424	N10°E	Forced Air Gas Furnace

*Volume of conditioned spaces used for air infiltration calculations.

TABLE 2

STATISTICAL RESULTS OF PHYSICAL MODEL P12

Size	β_o	r^2	CV%	rms error A/C	No. Observ.
KTSC	1.28	0.946	25.0	0.1253	389
ETSC	1.26	0.905	32.6	0.1597	265
CTSE	1.29	0.949	25.8	0.1036	504
HTSG	2.77	0.839	43.6	0.3610	179
HSLG	0.96	0.916	30.0	0.1270	157
SRSG	1.04	0.728	56.9	0.2321	226
KAWG	1.14	0.913	32.1	0.1445	30
OAMG	1.57	0.845	41.7	0.2112	39
PAEG	2.65	0.941	25.0	0.2052	90

TABLE 3

ADDITIONAL INFILTRATION IN CONDITIONED SPACE DUE TO CONNECTION TO FURNACE AREA

	With Gas Furnace		With Electric Systems (Chimney blocked)	
Site	ETSC	KTSC	ETSC	KTSC
No. Hours	91	37	174	352
β_o	1.36	1.42	1.21	1.26
R^2	0.95	0.91	0.88	0.96
CV%	23.1	34.4	37.1	21.6
Rms error A/C	0.13	0.24	0.17	0.10
Increased Infiltration	+12.4%	+12.7%	--	--

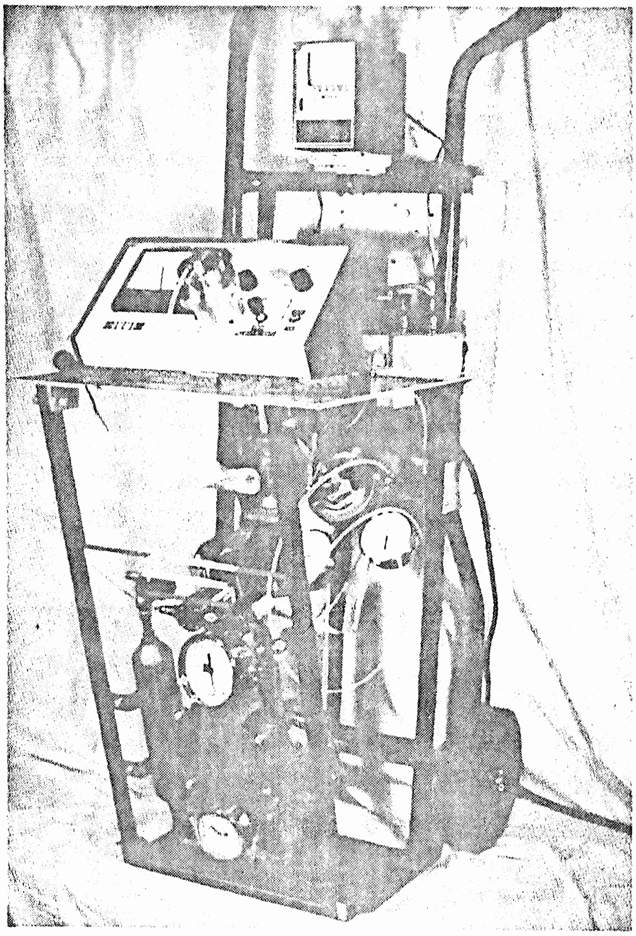

Fig. 1 Infiltration measuring device

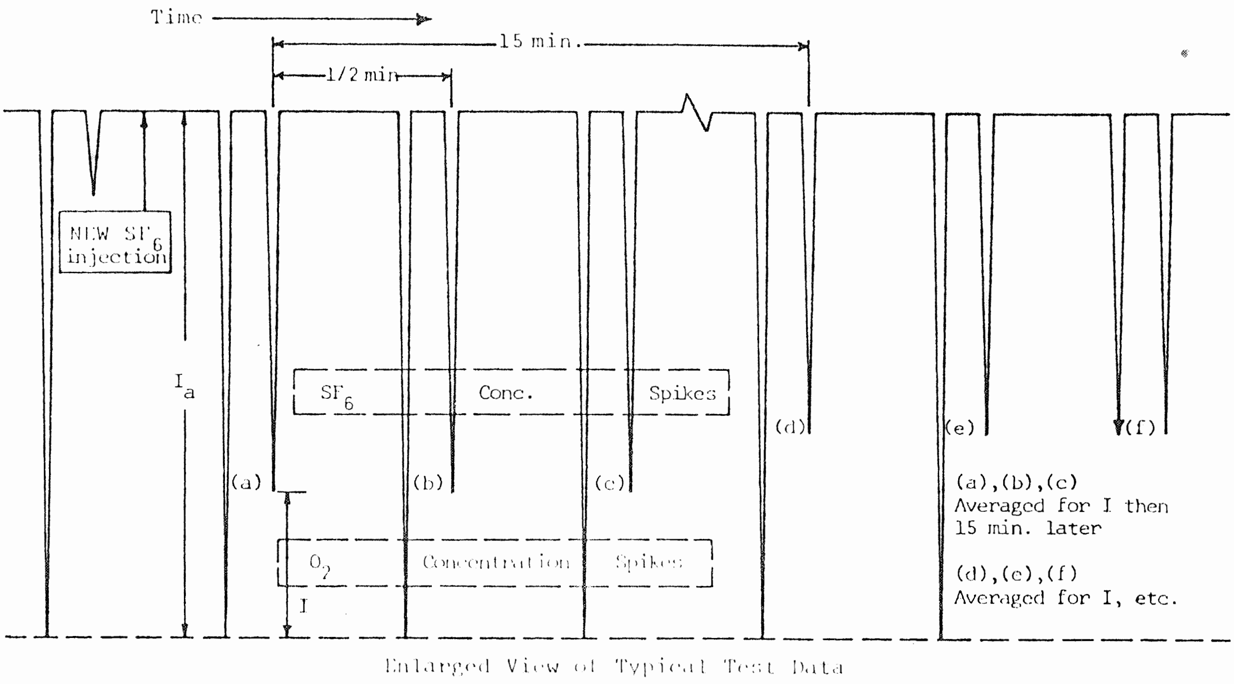

Fig. 2 Enlarged view of a typical chart record of air infiltration measurement

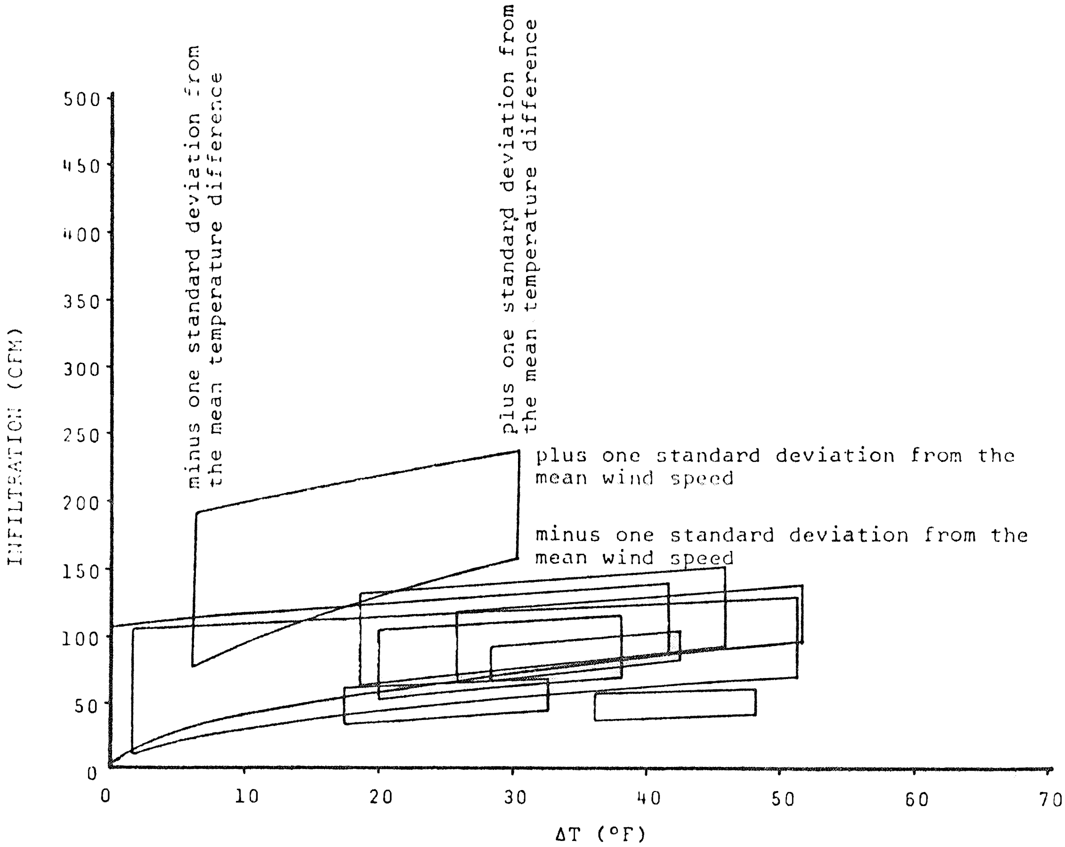

Fig. 3 Composite overlay of the measured data ranges

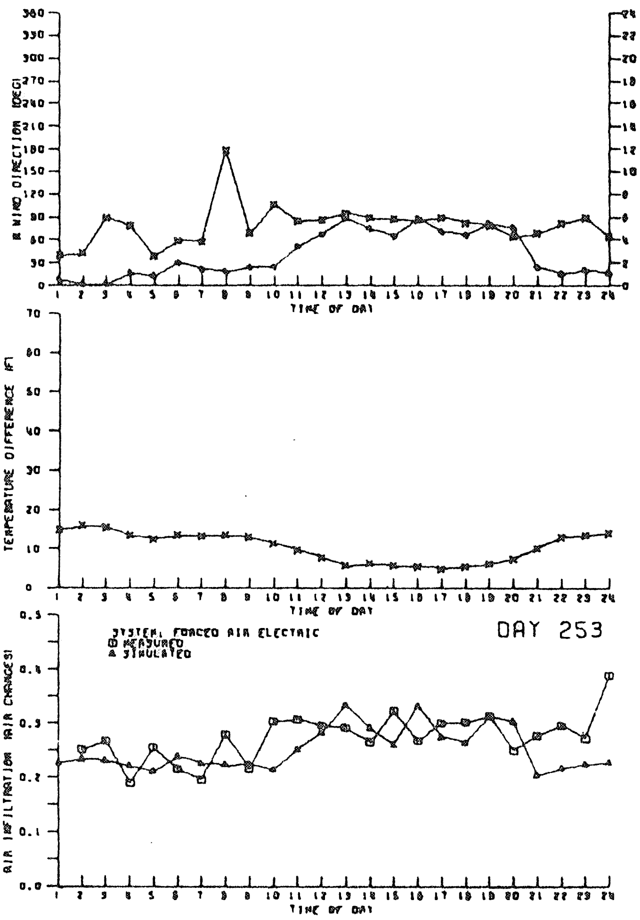

Fig. 4 Simulated vs measured air infiltration at site CTSE

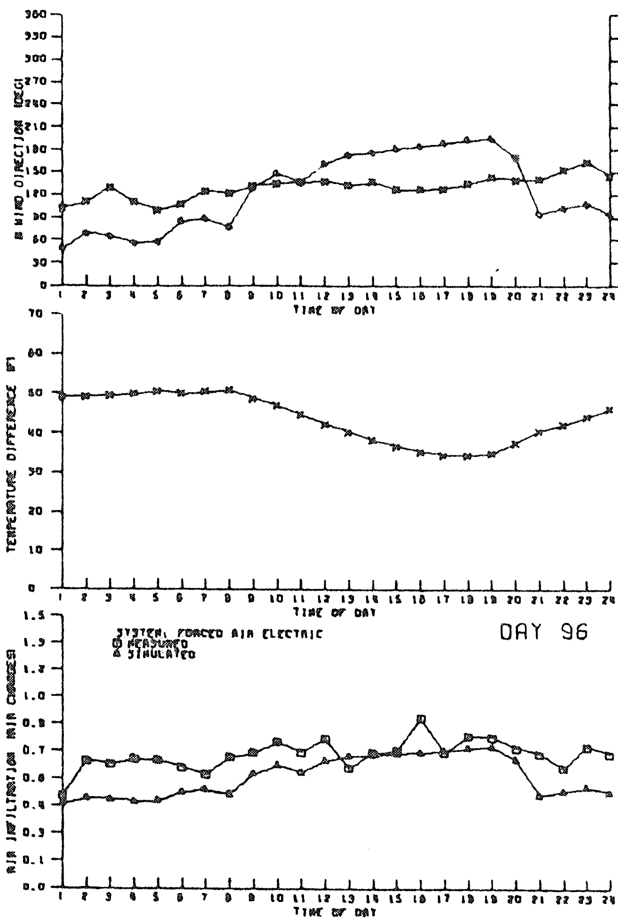

Fig. 5 Simulated vs measured air infiltration at site CTSE

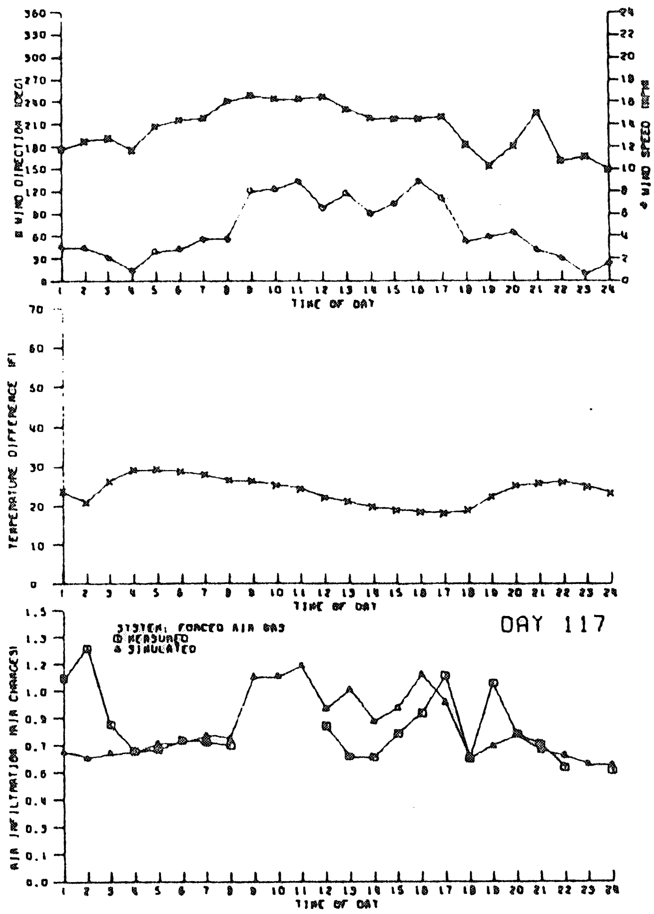

Fig. 6 Simulated vs measured air infiltration at site HTSG

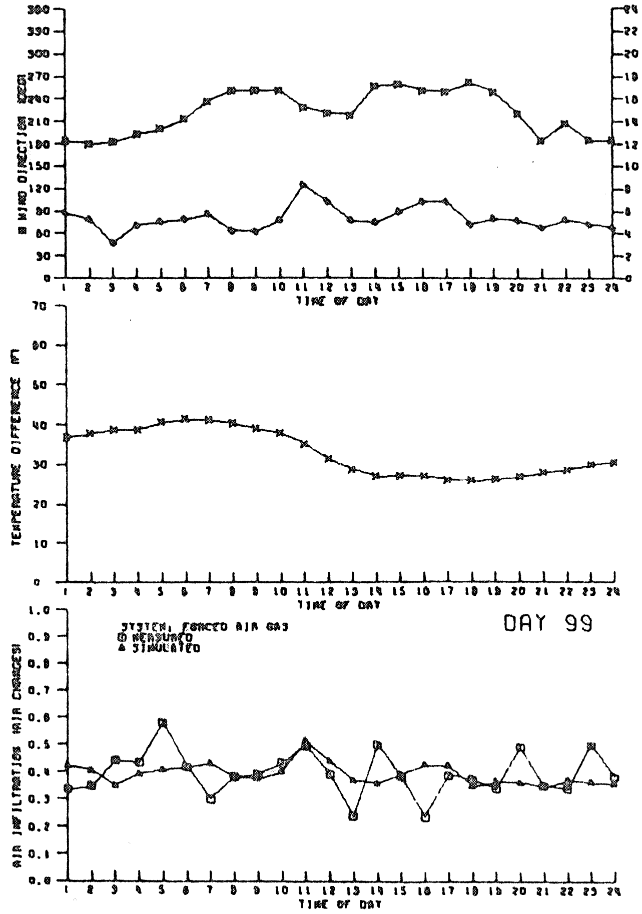

Fig. 7 Simulated vs measured air infiltration at site HSLG

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INPUT:
      ISYS= TYPE HEATING SYSTEM
            1= NO CHIMNEY
            2= CHIMNEY IN CONNECTED AREA
            3= CHIMNEY IN CONDITIONED SPACE
      VEL= WIND VELOCITY, MPH
      THER= INDOOR TEMPERATURE, F
      DBT= OUTDOOR TEMPERATURE, F
      IHOUS= TYPE HOUSE
             1= ONE STORY
             2= TWO STORY
             3= SPLIT LEVEL
      CRACK= TOTAL EQUIVALENT CRACK LENGTH, NORMALIZED TO
             NON-WEATHER STRIPPED, AVERAGE FIT, DOUBLE HUNG
             WOOD WINDOWS, FT

VARIABLES:
      CSTAT= STATISTICALLY DETERMINED COEFICIENT
      HZN= HEIGHT OF NEUTRAL ZONE, FT

OUTPUT:
      CFMINF= INFILTRATION, CFM


       ALGORITHM FOR HOURLY INFILTRATION

      IF(IHOUS-2) 10,20,30
   10 HZN=4.
      GO TO 40
   20 HZN=8.
      GO TO 40
   30 HZN=6.
   40 IF(ISYS-2) 50,60,70
   50 CSTAT= 1.87
      GO TO 80
   60 CSTAT= 1.43
      GO TO 80
   70 CSTAT= 2.21
   80 CONTINUE
      TDIFF=1./(DBT+460.)-1./(THER+460.)
      PDIFFT= 0.52*14.7*HZN*ABS(TDIFF)
      PDIFFU= 0.25491/(DBT+460.)*VEL**2.
      CFMINF=CSTAT*CRACK*(4.*PDIFFT+SQRT(2.)*PDIFFU)**.65
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Fig. 8