No. 1900

R. R. LASCHOBER
Associate Member ASHRAE

J. H. HEALY
Associate Member ASHRAE

Statistical analyses of air leakage in split-level residences

Knowledge of the amount of air leakage into or from a structure is important for several reasons. One, it affects the sensible and latent loads within a structure and, consequently, the size of equipment required to maintain a given environment; two, it affects the cleanliness or odor-bearing properties of the air within the structure; and, three, definite amounts of air are needed for the safe combustion of fuel-fired appliances found in the structure.

At the present time, some laboratory data are available for determining air leakage through different types of windows, doors, and wall constructions. Because these data have been collected under controlled laboratory conditions and only for the effect of wind speed, their usefulness is often questioned when the data are applied to structures which are subjected to the combined effect of both wind velocity and temperature difference between the air within and without the structure. It is this latter item, the temperature differential between the air within and without the structure, that is neglected when estimating infiltration by the "crack method" or "air change method," the two currently accepted estimating procedures.

Several papers dealing with the measurement of infiltration rates using helium as a tracer gas have been published,[1,2,3,4] and the studies reported in this paper also employed helium as a tracer gas. The tests conducted during the 1960-61 heating season investigated only natural infiltration rates. The measurements of relative changes in helium concentrations, necessary for determining infiltration rates, were made with a katharometer furnished by the National Bureau of Standards.

R. R. Laschober is Research Associate, University of Illinois, Urbana, Ill. J. H. Healy is Engineering Editor, American Artisan, Chicago, Ill. *This paper has been prepared for presentation at the ASHRAE 71st Annual Meeting, Cleveland, Ohio, June 29-July 1, 1964.*

OBJECTIVES

Since the two residences to be used in this study were research facilities used by industry associations to evaluate the comfort performance of heating and air-conditioning systems, the specific objective was to determine their infiltration rates in an effort to further define their thermal characteristics. In addition, the collected data were to be statistically analyzed to determine whether infiltration could be successfully related to outdoor temperature and wind conditions. The results obtained from successful statistical analyses were then to be compared to existing data and estimating procedures.

DESCRIPTION OF RESIDENCES

I-B-R Hydronic Research House: An exterior view of the I-B-R Hydronic Research House is given in Fig. 1. From this figure, it is evident that the house was of contemporary mid-western split-level design. In the next several paragraphs, the features of the house which are most pertinently related to infiltration will be discussed. A more complete description of the house is contained in References 5 and 6.

The known crackage present in the Research House, given in Table I, was provided by windows, doors, and sill plates. With the exception of the entry window, which was thermopane, all windows were single pane casement type windows. These windows were not provided with storm sash. In Fig. 2, which illustrates floor plans and other information related to the Research House, it can be seen that four doors were provided for exit from the house. Only two of these doors, however, led directly to the outside; the other two led to the garage and boiler room. The doors were weatherstripped but not provided with storm sash.

In all probability, the unusual construction of the second level roof of the Research House influenced air

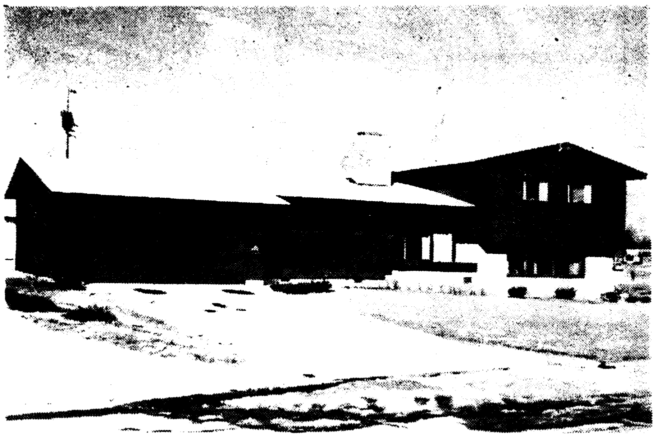

Fig. 1 Exterior view of I-B-R Hydronic Research House

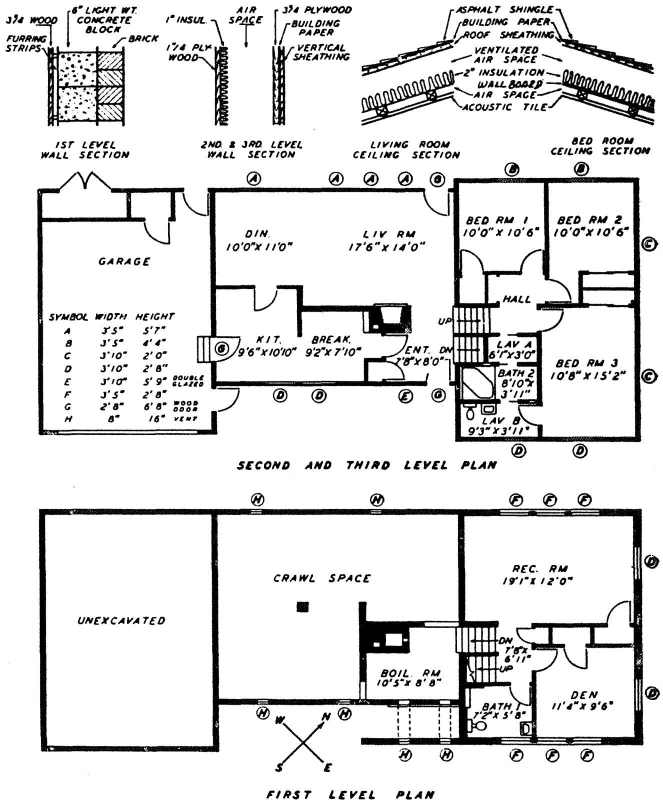

Fig. 2 I-B-R Hydronic Research House floor plans and miscellaneous construction details

leakage. A partial cross-section of this cathedral type ceiling is shown in Fig. 2. As this figure shows, ventilation air entering either soffit opening was free to flow between the roofing and a 2-in. blanket of insulation covering the interior fibrous acoustic tile ceiling. Prior to conducting the tests reported in this paper, a polyethylene film was secured between the insulation and nailers to prevent the flow of any air which may have passed around the insulation from continuing through the porous ceiling and into the room. If it had been possible to install this barrier in one continuous piece, the flow of air into the room through the ceiling would have been eliminated. However, it was necessary to use seams, and the second level ceiling remained at potential source of infiltration.

With the exception of the first level walls, all walls of the house were of frame construction, contained 1 in. of batt-type insulation, and had a 4-mil polyethylene film secured to the inside of the studding prior to adding the inside finish. The inside finish was 1/4 in. removable plywood paneling used in all rooms with the exception of the kitchen and breakfast rooms where 3/4 in. plywood was used. The first level walls which were not provided with a polyethylene film were uninsulated masonry walls with an inside finish of 3/4 in. wood paneling secured to 2-in nailers.

The heating system used while infiltration tests were being conducted was a three zone, series loop, valance system. The valance system is a system which uses finned-tube radiation installed at near ceiling height for heating the living area. This system is especially designed for both heating and cooling and a full description of it and its performance in the Research House is given in Reference 6. Each of the three levels of the house constituted a zone and was equipped with a thermostat. The thermostat of each zone effected the operation of its circulator whenever there was a demand for heat. The water temperature of the gas-fired boiler was governed by a high limit control. During winter operation, the boiler room vents were open, thus providing the burner with an adequate supply of outdoor air for combustion. For this reason, it is quite unlikely that the operation of the boiler affected measured infiltration rates.

Fig. 3 shows a site plan of the housing adjacent to the I-B-R House. Since the house was located in an

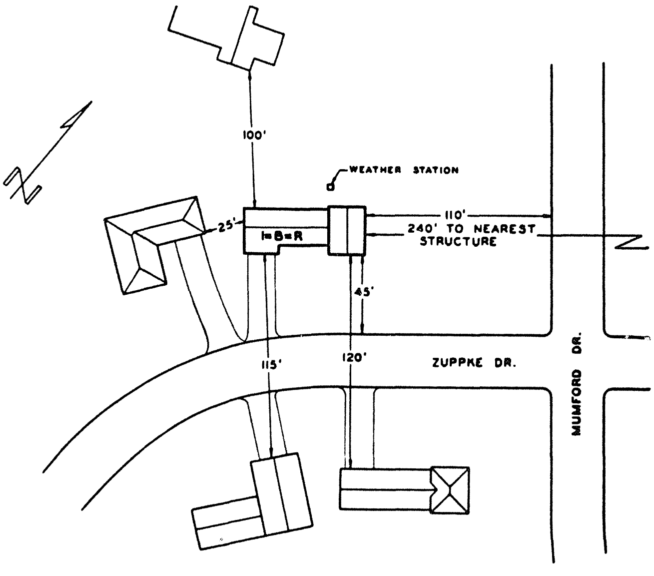

Fig. 3 Site plan of I-B-R Hydronic Research House

area which was experiencing new residential development, there were few objects outside the house which could be considered as having an effect on infiltration. The closest residence was 25 ft to the southwest. However, as seen in Table I, the southwest exposure of the house had little crackage, so in all probability, this building had little effect on infiltration. The closest building to the southeast was approximately 115 ft away, while over 100 ft of separation was provided on both the northeast and northwest exposures. Surrounding trees and shrubbery

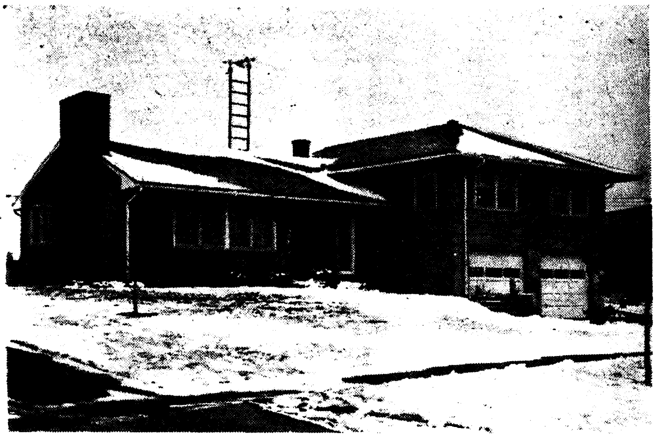

Fig. 4 Exterior view of NWAHACA Research Residence No. 4

were all saplings and had little, if any, effect on the house.

Warm Air Research Residence No. 4: The second residence used in the investigation was also a split-level design. Research Residence No. 4 was constructed to specifications provided by a building contractor, therefore, the house represented construction details and materials common to moderately-priced split-level structures. However, an electric heating investigation was conducted concurrently with the infiltration study, and the Residence was more thoroughly insulated than was common practice. Fig. 4 shows an exterior view of the Residence, and a floor plan showing room dimensions and orientations is shown in Fig. 5.

The lower level consisted of the family room, bath, instrument room,* garage, and utility room. The walls were composed of masonry blocks, 2-in. by 4-in. studs (furring strips), 3 in. of batt-type insulation. and interior plywood panels. Family room windows were the out-swinging awning style with removable double glazing. The window in the garage was also an awning type, and the instrument room contained fixed single-pane glass without storm sash.

The middle level included the living room, dining room, and kitchen. The exposed walls on this level were typical frame construction which included cedar shingles, insulating sheathing, 2-in. by 4-in. studding, 2 in. of batt-type insulation, and drywall panels for the finished interior. The ceiling contained 6 in. of batt-type insulation. All windows on the middle level were the horizontal sliding type with the exception of one window in the kitchen which was a casement style. The windows were all equipped with removable double glazing. The sliding glass doors in the dining room were composed of fixed double glazing with a metal frame.

The upper level contained four bedrooms and two baths. The exposed walls were identical to the middle level, but the upper level ceiling contained 7 in. of batt-type insulation. Each bath contained a casement window with removable double glazing, and the bedrooms contained double hung windows with separate storm sash.

The crawl space walls were composed of masonry

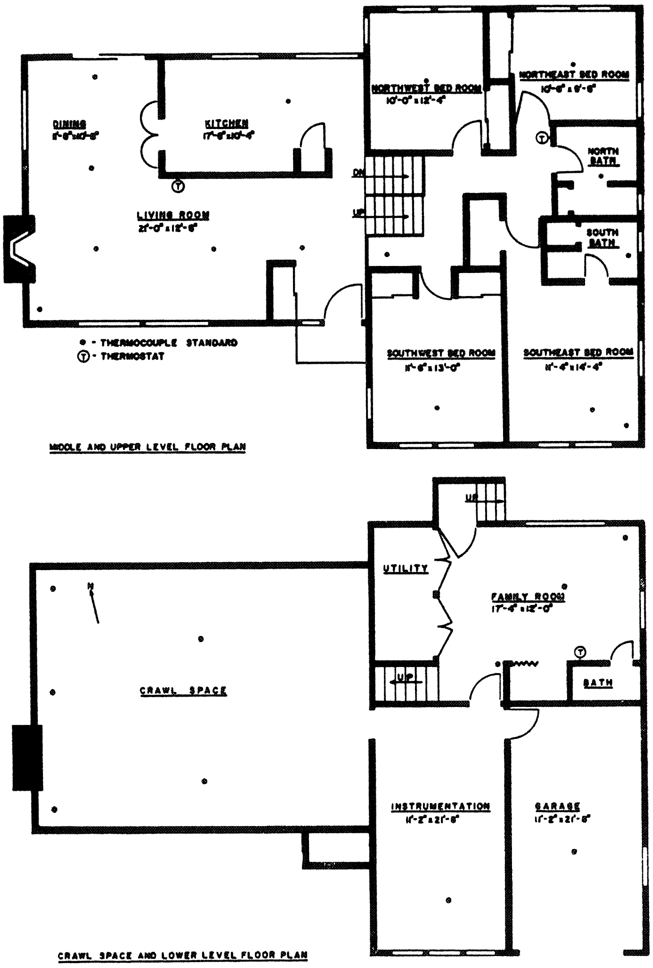

Fig. 5 NWAHACA Research Residence No. 4 floor plans and room dimensions

blocks and 2 in. of expanded polystyrene board-type insulation. All vents were closed and sealed as the space was heated.

All windows were of wood-frame construction and weatherstripped. The front exterior door on the middle level and the rear exterior door on the lower level were provided with storm doors. In addition, the door between the garage and instrument room was weatherstripped and provided with a threshold similar to an exterior door. All the batt-type insulation contained an attached vapor barrier, and no additional barrier was incorporated.

There were 1,930 sq ft of living area and the house

Table I Directional Distribution of Crackage for Research Residences*

I-B-R Hydronic Research House		NWAHACA Residence No. 4	
Direction of Exposure	Crackage ft	Direction of Exposure	Crackage ft
Northwest	245.5	North	253.5
Northeast	75.3	East	124.8
Southeast	172.7	South	231.8
Southwest	36.0	West	76.5
Total	529.5	Total	686.6

* Includes sill plate crackage

* *The instrument room was originally one portion of a two-car garage. Because of space demands for instruments, the area was altered and one garage door was sealed and insulated.*

volume was calculated to be 18,655 cu ft, including the crawl space volume of 1,625 cu ft. The heat loss of the structure was computed to be 64,900 Btuh, or 33.7 Btuh per sq ft for an 80 F indoor-outdoor temperature difference.

There was a total of 686.6 ft of crack around doors, windows, and sill plate. Table I lists the measured feet of crack for each exposure. A comparison of crackage for these exposures showed that the north and south sides (long sides) contained approximately the same crackage with 37 and 34% of the total, respectively. The narrow sides (east and west exposures) combined, contained less than 30% of the total crackage, and the west exposure had 11% and the east exposure contained 18%.

The heating system during the infiltration study consisted of a full perimeter air distribution system used in conjunction with a gas-fired or electric furnace. The central conditioning equipment was located in a utility room adjacent to the family room on the lower level. During tests with the electric furnace in operation, the chimney flue was sealed.

Residence No. 4 was located in a new housing subdivision composed of one-family units. The site plan shown in Fig. 6 illustrates the orientation of the Residence and its relationship to adjacent homes. Because of the recent development of the community, there were no mature trees or shrubs which could alter the influence of the wind. The terrain was completely flat, and it was typical of the central Illinois area.

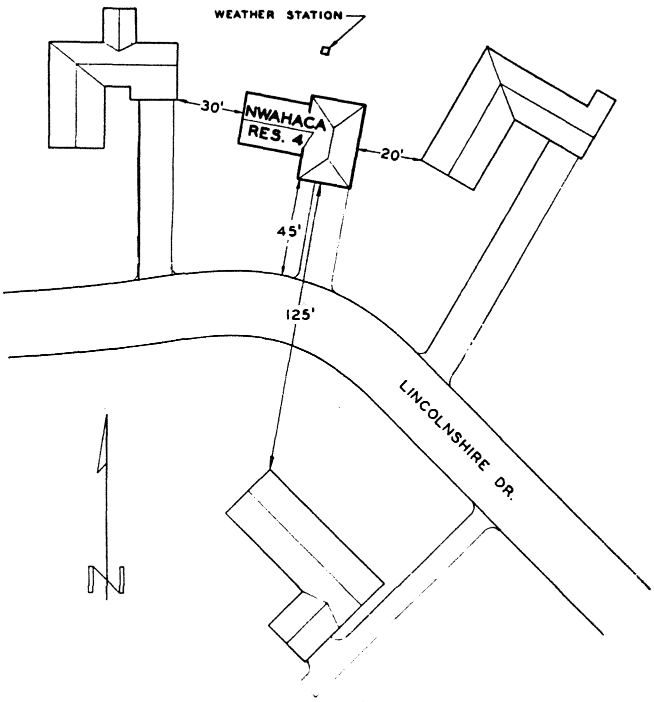

Fig. 6 Site plan of NWAHACA Research Residence No. 4

INSTRUMENTATION AND TEST PROCEDURE

The principal instrumentation consisted of the portable infiltration meter, designed and furnished by the National Bureau of Standards, used for measuring relative changes in helium concentrations. This device, which is more fully described in another publication,[7] contained a number of air sampling probes connected electrically to a console consisting of a galvanometer and a station selector. The console allowed the probes, located in various rooms, to be monitored at a central location.

In addition to helium concentrations, wind speed and direction, as well as indoor and outdoor temperatures were measured on site at each Residence with the complete outdoor weather stations and thermocouples already installed in these research facilities. Each house contained several hundred temperature measuring stations, although only ten to fifteen of these were pertinent to the infiltration study.

For each infiltration test, a sampling probe was positioned 30 in. above the floor in the center of each room (except baths). Helium was introduced into all levels of the houses until a concentration of approximately 2% was obtained. In the I-B-R Research House, the helium was introduced successively into individual rooms by use of a long hose connected to a pressure regulator and cylinder of helium. In Residence No. 4, helium was introduced into the return side of the air distribution system and was circulated by a centrifugal blower to other portions of the house.

The dilution or change in the helium concentration in each room was observed and recorded every 5 min, while temperatures at the 30-in. level in each room as well as outdoor temperature, wind speed, and direction were recorded every 10 min. The average duration of a test period was approximately 1½ hr. Throughout the period, all windows and exterior doors were closed, and no mechanical outdoor ventilation or exhaust fans were employed.

THEORY AND METHOD OF ANALYSIS

Ignoring the precision with which the relative concentration of a tracer gas can be measured, the accuracy of infiltration rates determined by the tracer gas technique is also a function of the similarity in behavior between the tracer gas and the gas within the volume being tested. Ideally, therefore, a tracer gas having a density, vapor pressure, and diffusion rate equal to the test sample should be used. Helium, when used as a tracer gas in air does not completely satisfy these requirements. However, since a small percentage of helium was used, it was assumed that the error encountered in the observed infiltration rates would be of little significance.

In addition to the above physical characteristics, the accuracy of infiltration rates determined for multiroom structures is also a function of the correctness of the theory employed in analyzing the data. Generally, the theory employed in analyzing infiltration data assumes that the depletion in concentration of the tracer gas is affected only by the in-leakage of air containing no tracer gas and out-leakage of a mixture of air and tracer gas. Under such an assumption, the infiltration rate in air changes per hr of the volume under consideration is given by the equation:

$$I = (1/t_1 - t_2) \ln (C_1/C_2) \quad (1)$$

where

I = air changes per hr
$t_2 - t_1$ = time change in hr
C_1 = concentration at time t_1
C_2 = concentration at time t_2

From this equation, the concentration plotted on a logarithmic scale vs time on a linear scale yields a straight line, the slope of which is I. In a building made up of several rooms, this simple case of pure infiltration generally does not exist, and the given equation is greatly complicated by the interchange of air between rooms. The nature of the equation along with its derivations is given in Reference 1. Because the more complicated equation requires knowledge of the rate of flow of air between rooms, and since no attempt was made to determine this flow at the time the tests were being conducted, the data obtained for both houses were analyzed under the assumption that pure infiltration took place within every room.

For this study, individual room helium concentrations were plotted vs time on semi-log paper and the best straight line correlation was drawn through the data. The slope of this line was then determined in order to establish the room infiltration rate. Level infiltration rates and house infiltration rates were then calculated from an average of the room infiltration rates weighted on a volume basis. These weighted level infiltration rates (three for each house), and the overall house infiltration rates were recorded along with wind speed and direction and indoor-outdoor temperature difference data taken during the test.

For the purposes of analysis, the wind was subdivided into components. For any given wind direction and wall orientation, the effective wind component acting on the wall can be given by the following equation:

$$\text{Wind component} = (\text{Wind Speed}) \cos\theta$$

where θ is the angle between the actual wind direction and the normal to the wall.

In this analysis, negative wind components had no physical significance and were, therefore, ignored. Thus, no more than two sides of a building could be acted on simultaneously by the wind. A zero component was assumed to exist on the leeward sides of the building and on sides parallel to the wind direction. The test data for the I-B-R Research House are given in Table II. These data were collected while operating with a gas-fired heating system. The data collected for Warm Air Research No. 4 are given in Table III, with an additional indication made as to whether the Residence was being heated by a gas-fired or electric furnace at the time of the test.

The data for each of the two houses used in this study were subjected to three multiple correlation analyses, the computations of which were performed on a digital computer. The first multiple correlation analysis was designed to investigate the correlation between infiltration and ten independent variables, namely, with the indoor-outdoor temperature difference and the components of the four wind directions each taken to both the first and second powers. Thus, if all independent variables were of statistical significance, the equation best representing the infiltration rate could be given in the form:

$$I = A + B\Delta T + \sum_{i=1}^{4} C_i W_i + D(\Delta T)^2 + \sum_{i=1}^{4} E_i (W_i)^2 \qquad (2)$$

where

ΔT refers to indoor-outdoor temperature difference, F
W_i refers to the wind component acting of the i^{th} wall
C_i and E_i are constants associated with the linear and quadratic terms of the i^{th} wall
$i = 1,2,3,4$ may be thought of as representing the directions of the wall normals, i.e., N, S, NE, NW, etc.
and A, B, C, D, and E's are constants determined from the analysis

If the analysis revealed that some independent variable was not significant in determining infiltration, it would not be included in Eq. (2). In other words, it is possible for the right side of Eq. (2) to contain less than eleven terms.

The second multiple correlation analysis was de-

Table II Infiltration Data Winter 1960-61
I-B-R Hydronic Research House

Test No.	In-Out ΔT	Wind Speed mph	Wind Direc.	Wind Components—mph NW	NE	SE	SW	Measured Infiltration Air Changes Per Hr 1st	2nd	3rd	House
31	46.3	6.5	SW	——	——	——	6.50	1.90	0.44	0.52	0.88
32	74.7	14.6	WNW	13.49	——	——	5.59	4.04	1.39	1.85	2.30
33	73.2	2.2	SW	——	——	——	2.20	2.02	0.63	0.82	1.08
34	73.2	8.8	SW	——	——	——	8.80	2.68	1.16	1.56	1.71
35	44.8	3.2	SW	——	——	——	3.20	2.28	0.61	0.99	1.10
36	70.4	14.2	W	10.04	——	——	10.04	4.58	2.05	1.85	2.67
37	46.2	11.0	ENE	——	10.16	4.21	——	3.40	1.08	1.13	1.74
38	57.3	14.4	NW	14.40	——	——	——	4.38	1.72	1.62	2.43
39	51.0	12.6	E	——	8.91	8.91	——	2.83	1.18	0.96	1.56
40	47.9	9.3	NW	9.30	——	——	——	2.86	1.41	1.13	1.71
41	12.6	9.0	WNW	8.32	——	——	3.44	1.72	1.50	0.87	1.33
42	24.0	1.0	NW	1.00	——	——	——	0.89	0.45	0.51	0.60
43	33:7	1.8	N	1.27	1.27	——	——	1.15	0.50	0.50	0.68
44	16.2	11.3	NW	11.30	——	——	——	2.59	1.11	0.97	1.47
45	−0.8	13.4	SSW	——	——	5.13	12.38	0.96	1.25	0.69	0.96
46	20.1	4.4	W	3.11	——	——	3.11	0.61	0.47	0.34	0.46
47	3.4	4.3	W	3.04	——	——	3.04	0.58	0.54	0.42	0.51
48	11.0	6.1	ESE	——	2.33	5.64	——	1.23	0.81	0.69	0.88
49	14.7	13.8	E	——	9.76	9.76	——	1.23	0.63	0.86	0.88
50	16.4	5.1	NE	——	5.10	——	——	0.66	0.36	0.34	0.42
51	−1.7	10.6	WSW	4.06	——	——	9.79	0.45	0.47	0.77	0.57
52	1.0	2.5	E	——	1.06	1.06	——	0.40	0.24	0.34	0.32

signed to investigate the correlation between infiltration and only the first power of indoor-outdoor temperature difference and the four wind directions. Thus, if all independent variables were of significance in this analysis, the equation best representing the infiltration rate would not include the last two terms on the right of Eq. (2). For the third multiple correlation, the analysis was further simplified by the grouping of wind components. This analysis considered a given wind component to have the same effect when acting on either of two opposite walls. Since both Residences were rectangularly shaped, it seemed reasonable to refer to two opposite sides as narrow sides and the remaining two sides as long sides. Thus, an equation in the following form could be expected:

$$I = A + B\Delta T + \sum_{i=1}^{2} C_i W_i \qquad (3)$$

where

$i = 1,2$ now has the meaning of either a long or narrow side wind component

Since the data for Residence No. 4 were also analyzed to determine whether the heating system had any effect on infiltration, any significant difference between the two fuels used would lead to the inclusion of another variable in Eqs. (2) and (3).

RESULTS OF ANALYSES

Throughout the remainder of this paper, use will be made of the t-distribution and the F-distribution for the purpose of making various tests of significance. Tabulations of t and F values over a range of degrees of freedom and critical levels of significance can be found in most statistics texts. The values used in this text were obtained from the Second Edition of "Statistical Tables for Biological, Agricultural and Medical Research," by Fisher and Yates.

Use of the t or F-distribution is made by comparing the ratio of the variable to its standard error with the t-distribution, or by comparing the ratio of two variances with the F-distribution. The generally accepted criterion for assigning levels of significance will be employed. That is, if the value of the calculated ratio is less than the value given at the 5% level, the phenomenon being tested is assumed to be caused by chance, and hence insignificant; if the ratio lies between the tabulated 5% and 1% levels, the phenomenon is said to be significant; and, if the ratio is greater than the tabulated 1% level, the phenomenon is said to be highly significant.

Hereafter, values of t and F will be specified in the following manner.

$$t_{n,cr} = t'$$
$$F_{n_1,n_2,cr} = F'$$

where:

- t' or F' refer to the tabulated value of t or F at the critical level indicated by the last subscript cr
- n = degrees of freedom used for the t-test
- n_1 = degrees of freedom used in the numerator for the F-test
- n_2 = degrees of freedom used in the denominator for the F-test
- cr = critical level specification

Table III Infiltration Data Winter 1960-61
NWAHACA Residence No. 4

Test No.	In-Out ΔT	Wind Speed mph	Direc.	Wind Components —mph N	E	S	W	Measured Infiltration Air Changes Per Hr 1st	2nd	3rd	House
Electric Heat											
61	62.9	0.0	W	—	—	—	—	0.49	0.64	0.27	0.52
62	71.2	12.5	NW	6.98	—	—	10.30	1.12	1.02	0.90	1.01
63	61.0	6.5	NE	5.39	3.63	—	—	0.58	0.56	0.38	0.54
64	46.7	6.8	E	1.36	6.65	—	—	0.49	0.52	0.32	0.47
65	38.4	15.4	ENE	8.58	12.70	—	—	0.70	0.62	0.52	0.61
66	37.5	10.0	N	9.80	—	—	1.99	0.60	0.68	0.52	0.61
67	35.1	11.3	W	—	—	2.25	11.04	0.62	0.45	0.36	0.47
68	38.5	7.8	ESE	—	7.64	1.55	—	0.16	0.22	0.22	0.20
69	28.6	14.7	SW	—	—	12.25	8.20	0.80	0.66	0.64	0.70
70	30.4	7.6	ENE	4.24	6.28	—	—	0.40	0.39	0.26	0.35
71	35.7	8.0	E	1.59	7.81	—	—	0.39	0.31	0.31	0.33
72	26.5	19.0	SSW	—	—	18.60	3.78	1.98	1.41	1.51	1.60
73	38.0	12.0	ESE	—	11.75	2.39	—	0.53	0.43	0.41	0.45
74	17.1	15.4	NW	8.60	—	—	12.75	0.61	0.56	0.50	0.55
75	29.6	16.7	WNW	3.32	—	—	16.30	0.48	0.64	0.45	0.54
76	31.9	12.6	NNW	10.40	—	—	7.02	0.72	0.59	0.62	0.64
77	34.4	9.2	NNE	9.00	1.83	—	—	0.62	0.50	0.40	0.50
78	29.0	13.5	WSW	—	—	7.52	12.00	0.66	0.73	0.60	0.67
79	29.9	8.8	NW	4.91	—	—	7.29	0.31	0.28	0.15	0.24
80	33.0	7.2	NW	4.01	—	—	5.95	0.34	0.22	0.16	0.23
Gas Heat											
81	62.4	17.0	SW	—	—	16.05	9.50	2.61	1.57	1.38	1.79
82	60.7	19.7	E	3.92	19.30	—	—	1.06	0.77	0.81	0.86
83	30.2	15.0	WSW	—	—	8.38	12.41	1.59	0.87	0.71	1.01
84	35.6	18.0	ESE	—	17.60	3.58	—	0.70	0.76	0.68	0.71
85	29.9	16.8	ESE	—	16.40	3.34	—	0.60	0.52	0.50	0.53
86	35.6	13.0	NNW	10.75	—	—	7.25	0.80	0.99	0.49	0.78
87	35.0	11.4	WNW	2.26	—	—	11.15	0.61	0.52	0.37	0.50
88	13.4	22.8	SSE	—	12.70	18.80	—	2.40	1.40	1.11	1.44
89	17.4	6.0	ENE	3.35	4.96	—	—	0.36	0.27	0.28	0.30
90	27.2	13.1	ESE	—	12.75	2.61	—	0.76	0.35	0.36	0.47

For example, for 40 degrees of freedom, the t value at the 1% level can be represented as

$t_{40,0.01} = 2.704$

I-B-R Research House: The most meaningful information obtained from the three analyses of the infiltration data for the Research House are given in Table IV. In this table, Tests A, B, and C are used to designate whether 10, 5, or 3 independent variables were used to determine the infiltration rate. The independent variables for each test are included in the column headed "Variable," while the regressions of the infiltration on these variables and the standard error of estimate for the respective regressions are given in the appropriately headed columns. The absolute value of each regression coefficient to its standard error is given in the last column. It is the values of these ratios that are compared with the given t values for making fiducial statements.

Referring to the results for Test A, it can be seen that none of the coefficients of the independent variables attains a highly significant level, i.e., all R/e values are less than 3.11. Several are significant, R/e ratios greater than 2.20; however, as will be shown later, a much simpler model (one having fewer independent variables) can be used to specify infiltration in the Research House without a significant loss in precision.

Observation of the results for Test B reveals that the regressions of the temperature difference and the northwest wind component, possessing R/e ratios greater than 2.92, are highly significant. The regressions of all the other variables are of no significance. If only highly significant contributions are considered, this would suggest expressing infiltration in terms of indoor-outdoor temperature difference and northwest wind components. In order to be more general however, wind components were classified either as long-side or narrow-side, and the data were reanalyzed. The results of this analysis are indicated as Test C in Table IV.

From the results given for Test C, it can be seen that indoor-outdoor temperature difference and long-side winds both possessed R/e ratios greater than 2.88 and were thus highly significant. Narrow-side winds are shown to be of no significance. This would suggest writing the formula for infiltration in the form given by Eq. (3). Using the results of the analysis of Test C to evaluate the constant yields:

$$I = 0.1096 + 0.0164 \Delta T + 0.0839 W_L \qquad (4)$$

where

I and ΔT are the same as previously defined and W_L refers to a long-side wind

The most convenient means available for testing whether any information was lost by simplifying the model from that proposed by Test A to that proposed by Test C is an analysis of variance. Table V presents a convenient tabulation for making such an analysis. In this table, Test C is assumed to represent the accepted model having three degrees of freedom (one degree of freedom for each of its independent variables). Since Tests B and A contributed 2 and 5 additional independent variables respectively, these are the values which are entered in the "Degrees of Freedom" column corresponding to these tests.

The value given for Test C in the column headed "Sum of Squares" is the square of the multiple correlation coefficient obtained for Test C. The values given in this column for Test B and A are the respective differences between the square of their multiple correlation coefficient and that of previous test. Values of mean square were obtained by dividing the sum of squares by the degrees of freedom, while values of variance ratio for a specific test were obtained by dividing the mean square for that test by the mean square given for the deviation. Critical F values are also given with this table. The last subscript of the tri-subscripted F value refers to the critical percentage for which F is given.

From Table V it can be clearly seen that the only variance ratio of statistical significance is that for Test

Table IV Results of Multiple Correlation Analyses: I-B-R Hydronic Research House

Test A

Multiple Correlation Coefficient = 0.975300; Standard Error of Estimate = 0.150408

Variable	Regression Coefficient, R	Standard Error, e	Ratio, R/e
ΔT	0.02213	0.00841	2.6324
$(\Delta T)^2$	−0.00007	0.00011	0.6414
W_{nw}	0.10650	0.04679	2.2762
W_{ne}	−0.00137	0.08329	0.0165
W_{se}	0.19655	0.07408	2.6534
W_{sw}	−0.01334	0.05362	0.2488
$(W_{nw})^2$	−0.00112	0.00367	0.3049
$(W_{ne})^2$	0.00348	0.00826	0.4208
$(W_{se})^2$	−0.01772	0.00761	2.3291
$(W_{sw})^2$	0.00448	0.00467	0.9574

n-k-l = 11; $t_{11,0.05} = 2.20$, $t_{11,0.01} = 3.11$

Test B

Multiple Correlation Coefficient = 0.952965; Standard Error of Estimate = 0.206377

Variable	Regression Coefficient, R	Standard Error, e	Ratio, R/e
ΔT	0.01527	0.00215	7.0997
W_{nw}	0.09059	0.01183	7.6613
W_{ne}	0.03306	0.02863	1.1548
W_{se}	0.05374	0.02908	1.8479
W_{sw}	0.03543	0.01508	2.3489

n-k-l = 16; $t_{16,0.05} = 2.12$, $t_{16,0.01} = 2.92$

Test C

Multiple Correlation Coefficient = 0.942469; Standard Error of Estimate = 0.227633

Variable	Regression Coefficient, R	Standard Error, e	Ratio, R/e
ΔT	0.01641	0.00209	7.8481
W_L	0.08398	0.01149	7.3119
W_n	0.02062	0.01333	1.5475

n-k-l = 18; $t_{18,0.05} = 2.10$, $t_{18,0.01} = 2.88$

Table V Analysis of Variance: I-B-R Hydronic Research House

Model	Degrees of Freedom	Sum of Squares	Mean Square	Variance Ratio
Test C	3	0.888	0.2960	67.30
Test B	2	0.020	0.0100	2.27
Test A	5	0.043	0.0086	1.95
Deviation	11	0.049	0.0044	
Total	21	1.000		

$F_{3,11,0.001} = 11.56$ $F_{2,11,0.20} = 1.87$ $F_{5,11,0.10} = 2.45$

C. Test B's contribution approaches the 10% critical value of F, while Test A's contribution approaches the 20% critical value of F. From these results it may be concluded that the amount of information lost in reducing the model from that of Test A to that of Test C is negligible, and that Eq. 4 gives a good estimation of the infiltration rates in the Research House.

Warm-Air Research Residence: The data collected in Residence No. 4 were processed in a manner comparable to the data collected in the Research House. For Residence No. 4, however, the data included an additional variable to study the effects on infiltration of the two heating systems employed. In order to facilitate the processing of data in this manner, tests conducted while gas was employed as a fuel were assigned a value of (+1), while those for electricity were assigned values of (−1). The results of the three analyses made on Residence No. 4 are given in Table VI, with EG representing the heating system variable. Because of the manner in which the data were processed, the coefficients given for EG for each of the three tests given in Table VI are multiplied by (+1) for gas tests and (−1) for electric tests. In other words, the difference in infiltration between gas and electric tests given in air changes per hour is twice the value of the EG coefficient. Notation used in this table is the same as that used in Table IV.

For Test A, it can be noted that the type of heating system employed is highly significant, the square of a south wind is significant, and all other variables are of no significance in establishing the infiltration rate. For Test B, the east and west winds appear to be the least significant variables. As was true for the Research House, these least significant variables can be associated with the narrow-side of the building, and as could be expected, combining long-side and narrow-side wind components and performing Test C led to the conclusion that narrow-side winds were of little consequence. For Test C, the EG variable did not attain a highly significant level. Even though this occurred, the EG variable has been included in the infiltration equation given for Residence No. 4, Eq. (6).

Observation of the EG coefficient revealed that using gas instead of electricity as a fuel would have led to chargeable increases in infiltration rates of 0.15, 0.14, and 0.16 air changes per hr. for Tests A, B, and C, respectively. During the course of the 1960—61 heating season, the furnace draft diverter was traversed to determine the approximate quantity of air used for dilution of the products of combustion. Velocity measurements indicated that approximately 2,000 cu ft of air per hr passed through the diverter and up the gas vent. With an additional 1,320 cu ft of air per hr required for combustion,* the increase in air leakage for combustion-dilution air amounted to 0.19 house air changes per hr during furnace operation. Thus, good agreement existed between the data and the means employed for predicting the increase in infiltration chargeable to gas heating. This increase in air leakage was observed to occur principally on the lower level where the gas furnace was located.

Contrary to the results obtained for the infiltration analyses performed on the Research House, it can be shown that the reduction in model from Test B to Test C produced a significant loss in the precision for Residence No. 4. Again, this can be demonstrated best by an analysis of variance as given in Table VII. From this table, it can be seen that a large variance ratio was obtained in reducing the model from that of Test B to that of Test C. In fact, this variance ratio is larger

* *Based upon 15 cu ft of air for each cu ft of gas consumed.*

Table VI Results of Multiple Correlation Analyses: NWAHACA Residence No. 4

Test A

Multiple Correlation Coefficient = 0.980130;
Standard Error of Estimate = 0.076072

Variable	Regression Coefficient, R	Standard Error, e	Ratio, R/e
EG	0.07344	0.02399	3.0609
ΔT	0.00985	0.00846	1.1646
$(\Delta T)^2$	0.00001	0.00009	0.1415
W_n	−0.00481	0.02595	0.1853
W_e	0.00126	0.01611	0.0782
W_s	0.02054	0.01991	1.0319
W_w	−0.01028	0.01862	0.5521
$(W_n)^2$	0.00397	0.00230	1.7241
$(W_e)^2$	0.00038	0.00082	0.4635
$(W_s)^2$	0.00263	0.00102	2.5747
$(W_w)^2$	0.00211	0.00117	1.7950

n-k-l = 18; $t_{18,0.05} = 2.10$, $t_{18,0.01} = 2.88$

Test B

Multiple Correlation Coefficient = 0.965850;
Standard Error of Estimate = 0.099367

Variable	Regression Coefficient, R	Standard Error, e	Ratio, R/e
EG	0.07119	0.02593	2.7448
ΔT	0.01088	0.00153	7.1349
W_n	0.04207	0.00685	6.1429
W_e	0.00861	0.00537	1.6039
W_s	0.06931	0.00450	15.3942
W_w	0.01373	0.00557	2.4634

n-k-l = 23; $t_{23,0.05} = 2.07$, $t_{23,0.01} = 2.81$

Test C

Multiple Correlation Coefficient = 0.931911;
Standard Error of Estimate = 0.139094

Variable	Regression Coefficient, R	Standard Error, e	Ratio, R/e
EG	0.08259	0.03331	2.4795
ΔT	0.01049	0.00205	5.1300
W_L	0.06706	0.00579	11.5874
W_N	0.01414	0.00669	2.1142

n-k-l = 25; $t_{25,0.05} = 2.06$, $t_{25,0.01} = 2.79$

Table VII Analysis of Variance: NWAHACA Residence No. 4

Model	Degrees of Freedom	Sum of Squares	Mean Square	Variance Ratio
Test C	4	0.868	0.2170	98.70
Test B	2	0.065	0.0325	15.00
Test A	5	0.028	0.0056	2.54
Deviation	18	0.039	0.0022	
Total	29	1.000		

$F_{4,18,0.001} = 7.46$ $F_{2,18,0.001} = 10.39$ $F_{5,18,0.05} = 2.77$

than that indicated for the 0.1% level of significance, which indeed means that a highly significant contribution to the data is lost when this model reduction is made. It can also be seen in this table that reduction in model from Test A to Test B produces a variance ratio quite comparable to that for the 5% level of significance. This would indicate that quadratic effects of the independent variables tend to be of importance in determining the infiltration rates for this residence. Since the object of this study was to provide information for the practicing engineer, and further, since from the practical standpoint the loss in precision in establishing infiltration rates affected by model simplification (as indicated in Table VI) is well within acceptable engineering limits, the simplest model has been chosen.

From the results of Test C, the simplified equation for infiltration into Residence No. 4 can be given as follows:

$$I = -0.2734 + 0.0826\,EG + 0.0105\,\Delta T + 0.0670\,W_L \qquad (6)$$

where
EG refers to either gas (+1) or electric (—1) as the input fuel and the other quantities are the same as previously defined

INTERPRETATION OF RESULTS

Having obtained expressions for infiltration rates within two split-level residences in terms of temperature difference and wind, it would be of value to:

1 Determine whether there is any agreement between the results obtained for the two split-level residences tested.
2 Compare these results with those of previous investigators.
3 Determine whether the directional notation used to define wind effects can be replaced by a more rational parameter.
4 Compare the results of these studies with currently accepted estimating procedures.

To determine whether there was any agreement between results obtained for the two residences tested, a procedure quite comparable to an analysis of variance was followed. The objective of this analysis was to examine the coefficients of the independent variables used to define infiltration in an effort to determine their statistical relationship. The coefficients of the simplified equations for infiltration, given by Eqs. (4) and (6) were compared. The details of the procedure followed in this analysis are clearly evident in Table VIII. Since 18 degrees of freedom were used to establish the equation for the Research House and 25 degrees of freedom for Residence No. 4, a value of 43 was used in selecting t for purposes of comparison. From this analysis, it can be seen that the difference between the temperature coefficients approaches the 1% level of significance, which indicates that the values of the coefficients obtained for the effect of temperature difference were significantly different. It can also be seen that no significant difference is indicated between the coefficients for long-side winds, thus suggesting that a value of approximately 0.075 can be used as a coefficient relating the effects of the component of a long-side wind to infiltration. Because of this indicated similarity of wind coefficients, it would be of interest to see more data of this type collected in order to determine whether any generality exists over a large sampling of structures.

The reports of investigations made in residential infiltration prior to this study contain very little information relating infiltration to wind and indoor-outdoor temperature difference. To the writers' knowledge, information of this type exists in only one previous publication.[3] In the cited publication, the data were categorized and subjected to several approximations in an attempt to isolate wind and temperature effects. By using this procedure, the authors were able to indicate the approximate effect of wind and temperature on infiltration. In Table IX, a tabulation is given of these indicated coefficients obtained for two residences, along with the coefficients given by Eqs. (4) and (6). From this table, it can be seen that the temperature difference and wind coefficients currently obtained are considerably higher than those formerly obtained. This is not surprising, for the residences currently investigated contained considerably more crackage. Also, investigators familiar with the residences used for both investigations were unanimous in their feeling that the current investigation was performed in houses of considerably looser construction. It is of further interest to note that the coefficients established formerly follow a pattern comparable to those obtained in this study, that is, there is good agreement between the wind coefficients but not between the temperature coefficients. Since the former study did not employ a rigorous statistical analysis, it is impossible to determine whether their coefficients could be said to have been drawn from the same population.

Table VIII Analyses of Temperature Difference and Long-side Wind Coefficients

Temperature Difference

House	Regression Coeff.	Std. Error	(Std. Error)²
I=B=R	0.01641	0.00209	0.00000437
Res. No. 4	0.01049	0.00204	0.00000416
diff. =	0.00592	Sum =	0.00000853

$$t = \frac{0.00592}{\sqrt{0.00000853}} = 2.025 \qquad t_{43,0.01} = 2.697$$

Long-side Winds

House	Regression Coeff.	Std. Error	(Std. Error)²
I=B=R	0.08398	0.01149	0.00013202
Res. No. 4	0.06706	0.00578	0.00003341
diff. =	0.01692	Sum =	0.00016543

$$t = \frac{0.01692}{\sqrt{0.00016543}} = 1.314 \qquad t_{43,0.05} = 2.018$$

Table IX Comparison of Temperature and Wind Effect on Infiltration

House	Temperature Difference	Wind Speed
I=B=R	0.00325	0.0130**
NWAHACA Res. No. 2	0.00660	0.0120***
I=B=R	0.01641	0.08398*
NWAHACA Res. No. 4	0.01049	0.06706*

* Based on long-side winds. Wind velocity determined on sight and at time of test.
** Wind information obtained from local weather station. No consideration given to wind direction.
*** Wind speed determined on sight during test. No consideration given to wind direction.

In the discussion which preceded, it has been shown that the effects of wind on infiltration were quite well defined by taking wind direction into consideration. It was further shown that good correlation still existed even if only the components of wind acting on the long-side of the structure were considered. Obviously, this would only be true if either the physical dimensions of the structure or some other parameter associated with these dimensions were of prime importance in establishing infiltration. Currently, crackage is considered to be the parameter having the most influence on infiltration, and from Table I, it can be seen that the exposures which contributed the most to the statistical determination in infiltration rates also contained the majority of crackage. Since the Guide[8] indicates that in terms of air leakage 1 ft of weatherstripped crack is equivalent to approximately 250 sq ft of wall, it may be concluded that the window and door crackage accompanying the various exposures was primarily responsible for infiltration.

By comparing ratios of crackage for two exposures of either residence to the ratios of regression coefficients for the same exposures, it was possible to determine whether the relative values of measured crackage were in agreement with the relative values of measured infiltration as indicated by the regression coefficients. For example, if the crackage of one exposure were twice that of another, it could be expected that the infiltration through the former exposure would be approximately twice that through the latter for a given wind component. If the ratio of regression coefficients for these same two exposures were 2:1 (or approximately so), it could be concluded that the relative amounts of crackage for the two exposures were relevant in establishing infiltration rates.

From Table I, ratios of crackage for the Research House for exposure ratios NW:SE and NW:NE can be found to be 1.43 and 3.27, respectively. From Table IV, ratios of regression coefficients for the corresponding exposure ratios can be found to be 1.68 and 2.75. Using Tables I and VI in the same manner in order to obtain comparable ratios for Residence No. 4, values of crackage ratios for exposure ratios of S:N and S:W can be found to be 0.93 and 3.53; while ratios of regression coefficients for the same exposure ratios were 1.65 and 5.05. From this comparison, it can be seen that agreement between relative crackage and relative infiltration for the structures tested was not exact.

However, it must be pointed out that only the linear footage of crack was used in this comparison and no adjustment was made for the different size of crack present. No adjustment was made in this comparison because the authors felt that the latitude of judgment permitted in assigning values to crackage could lead to a variety of answers. Then too, both residences had unusual infiltration problems which are presently undefined and would tend to mask the efforts spent in making a more precise determination of crackage. In view of these considerations, it may be concluded that our present knowledge of the factors affecting infiltration is not complete, and it is not possible to accurately relate the available infiltration data strictly to crackage.

Currently, the two methods commonly employed for estimating air leakage into residences are the crack method and the air change method. Both of these methods, which are thoroughly discussed in the Guide,[8] provide a means for estimating the air leakage into a residence for some given design condition. If the location of the neutral zone is known, the crack method incorporates a provision for accounting for the effect which indoor-outdoor temperature difference has on infiltration. However, since the estimation of the neutral zone is based on the knowledge of the crackage within a building, use of the temperature effect is seldom made. Neglecting the temperature effect, the estimated air leakage rates for the Research House at its design condition obtained by using the crack method and the air change method, respectively, were 0.98 and 0.90 air changes per hr. (The design condition used for infiltration estimations in the Urbana area was an indoor-outdoor temperature difference of 80F coupled with a 15 mph wind.) For the same design condition, use of the crack and air change methods both led to an estimated infiltration rate of 0.90 air changes per hr for Residence No. 4. By use of Eqs. (4) and (6), it can be shown that the measured infiltration rates in the Research House and Residence No. 4 at the design condition are 2.76 and 1.65, respectively. These values are considerably higher than those obtained by estimation. However, if only the average effect of wind, as determined by this study, is considered (namely, 0.075 air changes per hr per mph wind change), then an increment in wind speed of 15 mph would result in a 1.125 hourly air change rate.

From the foregoing analysis, it is apparent that the use of methods currently accepted for estimating residential infiltration rates resulted in values considerably less than those indicated by tests. Moreover, it can be seen that for both residences these estimated infiltration values compared favorably with the portion of the total infiltration which the tests indicated to be chargeable to wind effect. Since only two residences were investigated, it is impossible to determine whether the occurrence of this agreement was the result of chance. However, it is obvious that the effect of indoor-outdoor temperature difference was of importance in establishing infiltration rates in these two split-level residences. Because a comparable relationship between wind and temperature effects has been reported previously,[3] it appears that more tests devoted to the investigation of infiltration phenomena should be conducted.

CONCLUSIONS

1. The application of statistical methods to the infiltration data obtained by use of the tracer gas technique permitted the infiltration rates measured in both of the residences tested to be closely predicted by consideration of prevalent outdoor temperature and wind conditions. The analyses for the two residences revealed that:

a. The temperature coefficients established for each residence were statistically different from each other.
b. The wind coefficients, based on long-side winds, were not statistically different. Based on a long-side wind component, an average air change rate of approximately 0.075 air changes per hr per mile per hr was indicated.
c. Due to difficulties encountered in assigning physical dimensions to crackage and to the present state

of our knowledge of infiltration phenomena, it was not possible to attribute infiltration to a parameter more rational than long-side wind.

2. Infiltration rates obtained in this investigation were higher than those obtained previously in single-story structures and more tightly constructed structures. A high dependence of infiltration rates on indoor-outdoor temperature difference was shown to exist. This same dependence had been implied in a previous publication.[3]

3. Using the currently accepted crackage and air change methods for estimating the air leakage within each of the residences led to values considerably less than those actually experienced. The estimating procedures only attempt to account for the effect of wind on infiltration, and if the total measured infiltration rates were subdivided into the portions which the tests indicated to be chargeable to wind and temperature effects, the estimated rates were in close agreement with the indicated rates chargeable to wind. This would further suggest the need for more investigations in the study of infiltration phenomena.

ACKNOWLEDGMENTS

The authors wish to acknowledge the cooperation of the two industry associations, I-B-R and NWAHACA, for the use of their research homes, and also the National Bureau of Standards for providing the portable infiltration meter and the helium used for the studies reported in this paper. Specifically, the authors acknowledge the individual efforts of Professor H. W. Norton, University of Illinois, for his guidance in preparation and analysis of the statistical data; C. W. Coblentz, National Bureau of Standards, for his instructions on tracer gas techniques; and to W. W. Youngblood, Master's Degree candidate, for his work in obtaining and compiling the test data.

REFERENCES

1. Dick, J. B., Experimental Studies in Natural Ventilation of Houses, Department of Scientific and Industrial Research, Building Research Station Note No. 180, Garston, Watford, England.
2. Dick, J. B., Measurement of Ventilation Using Tracer Gas Technique, ASHVE Journal Section, Heating, Piping and Air Conditioning, p. 131, May 1950.
3. Bahnfleth, D. R., Mosely, T. D., and Harris, W. S., Measurement of Infiltration in Two Residences, ASHAE Journal Section, Heating, Piping and Air Conditioning—Two Parts, Part I, June 1957; Part II, July 1957.
4. Jordan, R. C., Erickson, G. A., and Leonard, R. R., Infiltration Measurement in Two Research Houses, ASHRAE Journal, Vol. 5, pp. 71-76, May 1963.
5. Harris, W. S., and Laschober, Robert R., Research Progress Report 1959-60, The I-B-R Hydronic Research House, Mechanical Engineering Experiment Station, Research Series I-B-R-3, University of Illinois, Urbana, Illinois, June 1960.
6. Harris, W. S., and Laschober, R. R., Hydronic Heating and Cooling with Valance Units, University of Illinois, Engineering Experiment Station, Bulletin No. 466, 1963.
7. Coblentz, C. W., and Achenbach, P. R., Design and Performance of a Portable Infiltration Meter, ASHAE Transactions, Vol. 63, pp. 477-482, 1957.
8. Fundamentals and Equipment, ASHRAE Guide And Data Book, Chapter 24, Infiltration and Ventilation, pp. 425-426, 1961.

DISCUSSION

R. G. WERDEN, Glenside, Pa.: Did you get any observation of the possibility of any stack effect on the structure wherein the infiltration might be greater at the lower levels than at the upper levels?

AUTHOR LASCHOBER: Yes, we did. However, this point was not covered in the paper. In Tables II and III the measured infiltration rates obtained on each level for each of the residences are given. From these data, it can be observed that the lower level infiltration rates are, for the most part, greater than those for the other two levels. This would indicate the presence of stack effect.

A. B. NEWTON, York, Pa.: Have you had any plan to carry your study on into the cooling situation instead of just the heating situation?

AUTHOR LASCHOBER: We do not have plans to continue this work at this time. Initially, we had planned on carrying this on for a complete winter and summer at both the research residences. However, we had other difficulties in operations, and we never did complete a summer's work.

F. W. BENNETT, Annapolis, Md.: Was there any detectable difference between the hot water system and the warm air system in the infiltration rates?

AUTHOR LASCHOBER: I wouldn't suspect that there would be a difference due to the type of heating system used. Differences were experienced between the two residences; however, these were probably due to construction differences rather than heating system differences.

P. R. ACHENBACH, Washington, D. C.: Have you attempted a statistical correlation between air leakage rate and wind direction? Considering that the chimney effect of a house tends to produce air flow through a house in a vertical path, did you attempt to correlate the air leakage with the distribution of cracks in a vertical direction?

Do you see any possibility of introducing a temperature difference concept into the air leakage computations as recommended in the ASHRAE Guide And Data Book? In previous infiltration studies made at the University of Illinois, the results show that a change of one mile per hour in wind velocity caused about the same increment in air leakage as a change of 3 to 4F in the indoor-outdoor temperature difference. Did you make such a comparison in this study?

AUTHOR LASCHOBER: Well, to answer your first question. No, we did not attempt to make any correlation of infiltration with the distribution of vertical crackage.

To answer your second question. Since the infiltration studies performed on these two residences and two previously studied residences indicate that infiltration is affected by temperature difference, I have given some thought to the possibility of incorporating temperature difference effect into the procedures currently appearing in the ASHRAE Guide And Data Book. However, I believe more studies of this type are necessary before sound judgment can be made.

We didn't make such a comparison in this paper. However, that can be easily done by comparison of the coefficients that are given. For example, the infiltration equation for the I=B=R Residence, Eq. 4, indicates that the temperature difference and wind coefficients are given as 0.0164 air changes/HR-ΔT and 0.0839 air changes/HR-mph, respectively. Thus, the ratio 0.0839 to 0.0164 indicates that a one mph wind change is equivalent to a 5.12 temperature difference change. In a similar manner, it can be shown that a one mph wind change is equivalent to a 6.38 temperature difference change for Residence No. 4.