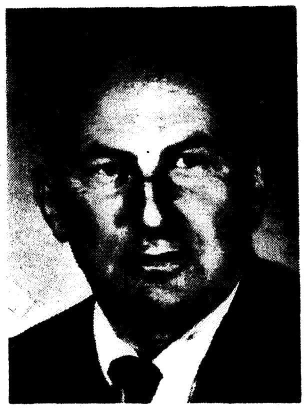
No. 1845

Field Measurements of Air Infiltration In Ten Electrically-Heated Houses



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At the request of the Rural Electrification Administration, of the U.S. Department of Agriculture, field measurements were made of air infiltration in ten electrically-heated houses in the region served by the Indiana Statewide Rural Electric Cooperative, Inc. The study was made to assist the Rural Electrification Administration in correlating computed heating loads with observed use of electrical energy for heating.

In planning the study, one and two-story brick and frame houses built over basements, crawl spaces, and concrete slabs on ground were considered to be representative of a majority of residential construction. Ten residences, comprising eight out of a possible twelve combinations of the above constructions, were selected for the study.

DESCRIPTION OF HOUSES

A summary of the significant data on the types of constructions, materials, and dimensions of the ten residences investigated is shown in Table I. This table indicates that there were four brick veneer, five frame, and one stone veneer buildings, of which six were one-story and four were two stories in height. Five buildings had basements, three had crawl spaces, one had a combination of basement and crawl space, and the one apartment was built on a concrete slab on ground. The apartment was an end unit, with three walls exposed to the weather, of a one-story building of brick veneer and frame construction. There were five practically new houses, and the ages of the others ranged from 20 to 46 years, with an average age of 31 years.

The floor area of the heated space in the buildings ranged from 598 to 1922 sq ft, with an average of 1370 sq ft. The heated volume of the residences averaged 10,820 cu ft. The ceiling heights of the houses ranged from 7 ft 6 in. to 9 ft 4 in. for the first floor and from 6 ft 6 in. to 8 ft 0 in. for the second floor in the four 2-story houses. Insulation was used in the walls and ceilings of all houses and in the floors of seven. Sheathing paper or a vapor barrier was used in all houses. Four of the five new houses and one 20-year-old house employed vapor barriers. Plaster or plasterboard was used as the interior finish for the ceiling and walls in all houses.

The total lengths of door and window cracks for each house also are shown in Table I. The computations were made from dimensions taken from the original floor plans for each house. The crack lengths for doors and single-hung windows were taken as the perimeter length of the opening, whereas that for a

Table I Dimensional and Construction Data of Residences

House	Size of Heated Space Floor Area sq ft	Volume cu ft	No. of Stories	Wall Materials[a]	Foundation Type	Age yrs.	Crack Length Doors ft	Windows ft
A	1220	9750	1	Brick Veneer	Crawl Space	20	57	219
B	1229	9830	1	Frame	Basement	30	38	280
C	1510	12,080	1	Brick Veneer	Crawl Space & Basement	New	38	90
D	1230	9520	2	Frame	Basement	20	38	279
E	1510	12,950	2	Frame	Basement	40	57	252
F	1658	13,240	1	Stone Veneer	Basement	New	91	231
G	1130	8460	1	Frame	Crawl Space	New	40	162
H	1696	13,220	2	Frame	Crawl Space	46	56	260
I	1922	14,480	2	Brick Veneer	Basement	New	39	176
J	598	4680	Apt.	Brick Veneer	Slab on Ground	New	38	48

[a] All houses of brick or stone veneer construction employed 4 in. of masonry on the outside of 2 in. x 4 in. frame and interior finish.

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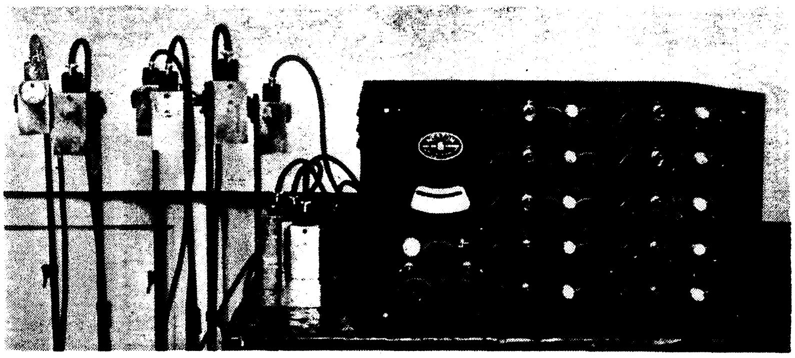

Fig. 1 Control console and sensing elements of portable helium infiltration meter

double-hung window was taken as the sum of the perimeter length and the meeting rail length. Neither sealed windows nor sealed window sections were included in the computation of the crack lengths.

TEST METHOD AND PROCEDURE

Air infiltration is defined as the air leakage of a building, through cracks and interstices around doors and windows and through the floor, walls, and ceiling, that cannot be directly controlled by the occupants. Ventilation comprises the controlled displacement of air in a building through openings, such as windows, doors, ventilators, and combustion heating devices, by either natural or mechanical forces. The magnitude of the air infiltration depends on the wind and temperature forces acting on the building, its height and exposure, the type of materials used, workmanship, and the condition of the building.

The air change rate of an enclosure is defined as the hourly volumetric rate at which air enters (or leaves) the enclosure divided by the volume of the enclosure.

The infiltration of air in each of the ten electrically-heated residences was determined by a tracer gas method.[1] By this technique, the rate at which fresh air enters a house is determined by introducing a small amount of a tracer material into the space and measuring the rate of change in concentration of the tracer material by means of one of its physical properties. The apparatus used was the portable infiltration meter developed at the National Bureau of Standards, consisting of a measuring and control console and ten sensing devices, as shown in Fig. 1.[2]

Approximately ½% of helium in relation to the total volume of the house was introduced after the test apparatus had been brought to temperature equilibrium with the air in the house. The helium was introduced into each room and was mixed with the room air by using several desk fans. The outside doors and windows were closed; closets and cupboards and all doors inside the living area were kept open during the test, so the concentration of tracer gas would decay in all of these spaces at about the same rate. The ten sensing probes were placed near the centers of the rooms about 3 ft above floor level, and readings were taken at each station at 5-min intervals for a period of 1 hr or more. During a test, the indoor and outdoor temperatures were measured, and the wind velocity and direction were observed in the vicinity of the house about 10 ft above ground. Two to four such infiltration tests were made in each dwelling at prevailing conditions over a period of about two days.

TEST RESULTS

A total of thirty infiltration tests was made in the ten houses. The data from two of these were discarded, however, because significant changes in the infiltration rates occurred during the test period, as a result of opening the outside doors.

It can be shown[2] that the air change rate in a single enclosed space during a selected interval is directly proportional to the natural logarithm of the ratio of the concentrations of the tracer gas at the beginning and end of the time interval, if the forces causing infiltration remain constant. Under these conditions, a constant infiltration rate would be represented by a straight line on semi-logarithmic graph paper. Thus, a practical way to determine the average infiltration rate from a series of measurements of tracer gas concentration in a given room is to plot the data on semi-logarithmic graph paper.

The change in relative concentration of the tracer gas with time at each station of observation during the twenty-eight tests made in the ten sample houses was plotted on semi-logarithmic graph paper to obtain an average air change rate, and to reveal the steadiness of the infiltration process. Two such graphs are shown in Figs. 2 and 3

Table II Summary of Room-by-Room Infiltration Data in Two Houses

Name of Room	Room Volume cu ft	Part of House Volume %	Air Change Rate, Related to Room hr^{-1}	Air Change Rate, Related to Whole House hr^{-1}
RESIDENCE C				
Liv. Room	2704	25.0	0.35	0.088
Kitchen	2448	22.7	0.40	0.091
Laundry	280	2.6	0.30	0.008
Bedroom 1	1768	16.4	0.32	0.052
Bedroom 2	1224	11.3	0.21	0.024
Bedroom 3	1016	9.4	0.32	0.030
Bath 1	848	7.9	0.48	0.038
Bath 2	512	4.7	0.32	0.015
TOTAL	10,800	100.0		0.346
RESIDENCE H				
Liv. Room	2182	15.1	0.93	0.141
Din. Room	2182	15.1	0.89	0.134
Kitchen	2433	16.9	0.79	0.132
Bedroom 1	1847	12.8	0.74	0.095
Bedroom 2	1794	12.4	0.45	0.056
Bedroom 3	1794	12.4	0.33	0.041
Bedroom 4	1674	11.6	0.62	0.072
Bath	522	3.6	0.51	0.018
TOTAL	14,428	99.9		0.689

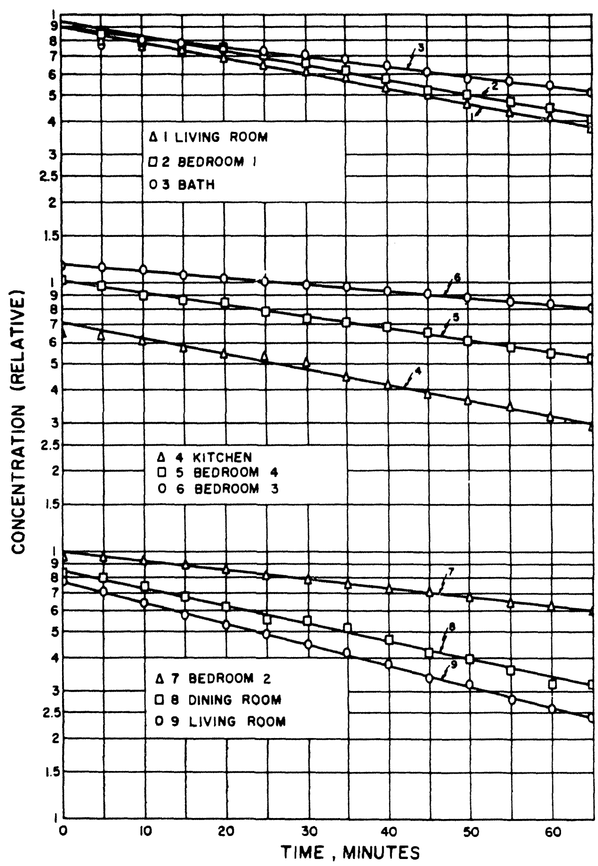

Fig. 2 Observed helium decay in the individual rooms of house H, a two-story frame structure with a crawl space

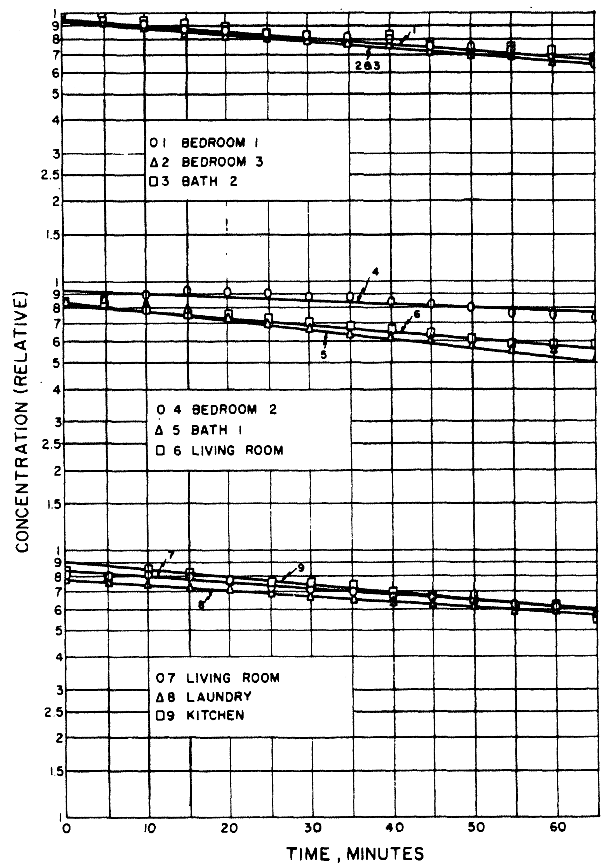

Fig. 3 Observed helium decay in the individual rooms of house C, a one-story brick veneer structure with combination basement and crawl space

to illustrate the results in a one-story and a two-story house, respectively. Figs. 4 and 5 show the floor plans of the houses from which the infiltration data in Figs. 2 and 3, respectively, were obtained. In Figs. 2 and 3, the change in relative helium concentration with time for each room of the house for a period of about one hour is shown, together with the identification of the house and each room of the house. The concentration curves are plotted in groups of three on a repetitive scale so each curve can be more readily delineated. In most instances, a straight line was a good representation of the decay curve. In the few cases where a straight line was not a good approximation of the decay curve, the data for these stations were not used in determining the average value for the house.

A summary of the room-by-room infiltration data is shown in Table II. The air change rate for each room was computed as the natural logarithm of the ratio of the concentrations at times 0 and 60 min taken from Figs. 2 and 3. When more than one sensing device was located in a given room, the air change rate was taken to be the average of the computed values for all the stations in that room. The air change rate for the entire house was computed as the sum of the products of the air change rates in the individual rooms and the corresponding percentage of the total house volume represented by each room. In cases where the helium concentration data for a specific room were not usable, the volume of that room was not included in the total house volume. This procedure is tantamount to assuming that the infiltration rate of any space for which the data were not available or could not be used was equal to the average infiltration rate for the rest of the house.

Table III is a summary of the average observed infiltration rate expressed in air changes per hr for each test, and shows the average wind velocity and prevailing direction, the inside-outside temperature difference, and an air change rate adjusted to a 10-mph wind velocity and an indoor-outdoor temperature difference of 40 F. The average wind velocities that prevailed during the air infiltration tests ranged from 6 to 15 mph, and the inside-outside temperature differences were between 20 and 64 F. The variation in outdoor conditions made it impossible to compare the observed air change rates of the ten houses directly. Enough tests were not made with any of the houses to evaluate exactly the effects of wind velocity and temperature difference on the infiltration rate. However, an approximate method for adjusting the observed values of infiltration rate of each building to a selected average climatic condition was used, as described in the following section.

DISCUSSION AND CONCLUSIONS

Published information[3,4] on infiltration measurements in two test houses at the University of Illinois, one a two-story brick veneer struc-

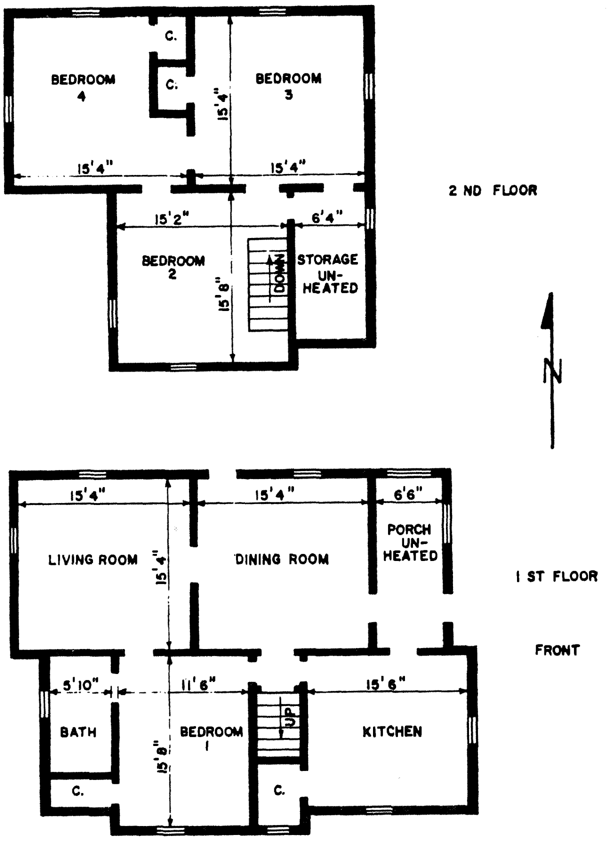

Fig. 4 Floor plan of house H, a two-story frame structure with a crawl space, 46 years old

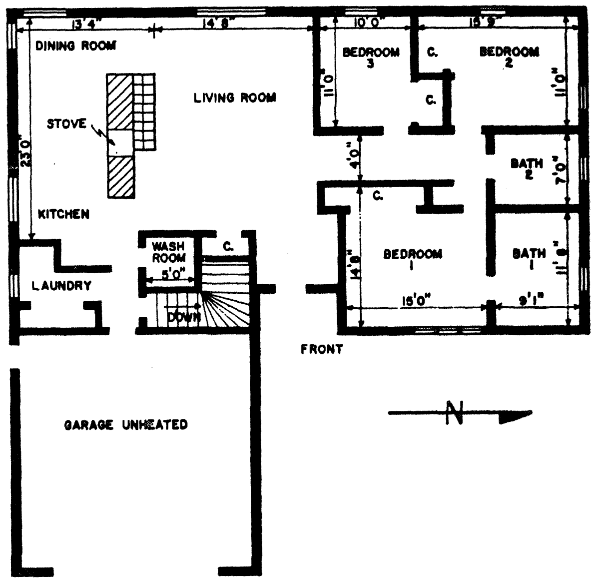

Fig. 5 Floor plan of house C, a new one-story brick veneer structure with a combination basement and crawl space

Table III Summary of Test Results

House	Test Number	Observed Wind Conditions Velocity mph	Direction	Indoor-Outdoor Temp. Diff. F	Observed	Infiltration Rate Adjusted[a] Each Test	Average
					Air changes per hr		
A	1	15	SW	45	0.84[b]	0.71	
	2	15	W	45	0.77[b]	0.65	
	3	15	WNW	48	0.77[b]	0.63	
	4	15	W	46	0.58[c]	0.48	0.62
B	5	6	N	42	0.71	0.78	
	6	6	N	43	0.56	0.61	
	7	11	S	43	0.91	0.86	0.75
C	8	11	SW	27	0.51	0.57	
	9	15	SW	23	0.42	0.44	
	10	10	SSW	23	0.35	0.43	0.48
D	11	13	SSW	24.5	1.14	1.24	
	12	12	SSW	20	0.84	0.99	
	13	10	SW	29	0.67	0.76	0.99
E	14	11	W	41	0.99	0.95	
	15	10	W	41.5	0.81	0.80	
	16	6	NW	44	0.76	0.81	
	17	11	N	45.5	0.94	0.87	0.86
F	18	6	WSW	54.5	0.55	0.53	
	19	12	WSW	49.5	0.39	0.34	
	20	8	WSW	46	0.23	0.23	0.37
G	21	6	NW	48	0.57	0.58	
	22	6	SW	50	0.42	0.42	0.50
H	23	6	NE-SW	38	0.74	0.85	
	24	6	SW	42.5	0.60	0.65	
	25	8	NW	53	0.69	0.64	0.71
I	27	11	W	46	0.52	0.48	0.48
J	28	6	NE	42.5	0.58	0.63	
	30	8	W	63.5	0.81	0.68	0.66

[a] Adjusted to uniform indoor-outdoor temperature difference of 40 F, uniform wind velocity 10 mph.
[b] Open exhaust vents in kitchen and bathroom.
[c] Closed exhaust vents in kitchen and bathroom.

ture over a basement and the other a one-story frame structure over a basement, indicated that the air change rate in each was directly proportional to the indoor-outdoor temperature difference and also to the wind velocity. The observed infiltration rates with no wind and no indoor-outdoor temperature difference were about 0.12 to 0.18 air change per hr in the two houses. The University of Illinois data showed further that an increase in wind velocity of 1 mph was equivalent to an increase in indoor-outdoor temperature difference of 2 to 4 F in its effect on the infiltration rate. Thus, an expression of the form of Eq. (1) can be used to approximate the effect of wind and temperature difference on the air change rate for these test houses.

$$I = A + BW + CT \qquad (1)$$

where

- I = hourly air change rate
- W = wind velocity, mph
- T = inside-outside temperature difference, F
- A = the air change rate with no wind and no temperature difference, hr^{-1}
- B, C = the increase in the air change rate per unit increase in wind velocity and temperature difference, respectively

Based on average values observed in the two test houses investigated by the University of Illinois, Eq. (1) would become:

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

A wind velocity of 10 mph and a temperature difference of 40 F approximated the averages of the observed outdoor conditions during the tests of the ten houses in Indiana used in this investigation. If it is assumed that the proportional change in air infiltration of these houses was similar to that reported by Bahnfleth for the two University of Illinois houses, Eq. (2) can be used to adjust the observed data from this investigation to the average wind velocity and temperature difference cited above by the following relationship:

$$I_1 = \frac{0.48 \times I}{0.15 + 0.013W + 0.005T} \qquad (3)$$

where I, W, and T are the observed values of air change rate, wind velocity, and temperature difference for any test and I_1 is the air change rate adjusted to a wind velocity of 10 mph and a temperature difference of 40 F.

Table III shows the adjusted value of air change rate for each test and each house based on Eq. (3). These adjusted values should be considered as approximate values because the absolute and relative values of the constants A, B and C in Eq. (1) probably differed from house to house. However, the adjusted values are probably more nearly comparable with each other than the measured values. The measured air infiltration rates of the two test houses[3,4] at the University of Illinois for these same wind and temperature conditions were 0.38 air change per hr for the two-story brick veneer house over a basement and 0.55 air change per hr for a single-story frame house over a basement, equal in each case to about three times the air change rate with no wind and no temperature difference.

It will be noted in Table III that three tests were made of house A with kitchen and bathroom vents open, resulting in an average air change rate of 0.79 per hr, and one test was made with these vents closed with a corresponding air change rate of 0.58 per hr at nearly the same outdoor conditions. Since the volume of this house was 9750 cu ft, it appears that these two vents caused a combined ventilation of about 2050 cu ft per hr under the prevailing weather conditions.

Table IV summarizes the adjusted air change rates in relation to the type of wall material and foundation, building height, and age of the building in the order of ascending values of air change rate. It indicates that the infiltration rate ranged from 0.37 to 0.99 air changes per hr under the same conditions.

Since only one house in each category was tested, with the exception of two 2-story frame buildings, care should be exercised in drawing conclusions about categorical differences in airtightness of the different types of houses. However, Table IV shows that the air change rate of four of the new buildings was significantly lower than that of the older buildings. Although a general increase in air leakage might be anticipated as a house grows older because of deterioration of materials, it will be noted that one 20-year-old residence was among the five houses with the lowest air change rates. The new buildings were designed and constructed for electric heating systems, so it seems likely that efforts were made to keep the infiltration heat losses at a low level. A part of the windows in each of the new houses had fixed sections in them, and in house A, 20 years old, the windows in the living room had a fixed sash and all of the window frames were caulked into the masonry.

Considering the three house characteristics, other than age, listed in Table IV, it will be noted that the four houses with the highest air change rates were all of frame construction and three of the four were two stories in height. However, these same four houses were 20 to 46 years old, so it is impossible to judge whether age, height, or material of construction was the more significant with respect to the rate of air exchange by infiltration.

AIR INFILTRATION BASED ON WINDOW AND DOOR CRACK LENGTHS

The air infiltration per unit crack length was calculated for the ten residences at the selected condition of 10 mph wind velocity and 40 F inside-outside temperature difference. Only doors and openable windows were used in computing the crack lengths. The air infiltration rate through the cracks was calculated by the following formula:

$$L = \frac{V \times I}{C} \qquad (4)$$

where
L = air infiltration rate, cu ft/hr (ft of crack length)
V = volume of heated space, cu ft
I = observed air change rate per hr adjusted to 10 mph wind, 40 F temperature difference
C = total crack length, ft

Table IV Adjusted* Air Change Rate in Relation to Construction Features of Houses

House	Air Change Rate/hr	Age of Building	No. of Stories	Wall Material	Type of Foundation
F	0.37	New	1	Stone Veneer	Basement
C	0.48	New	1	Brick Veneer	Crawl Space & Basement
I	0.48	New	2	Brick Veneer	Basement
G	0.50	New	1	Frame	Crawl Space
A	0.62	20 yrs.	1	Brick Veneer	Crawl Space
J	0.66	New	Apt.	Brick Veneer	Slab on Ground
H	0.71	46 yrs.	2	Frame	Crawl Space
B	0.75	30 yrs.	1	Frame	Basement
E	0.86	40 yrs.	2	Frame	Basement
D	0.99	20 yrs.	2	Frame	Basement

* Adjusted to 10 mph wind velocity and 40 F temperature difference.

The sample houses are listed in Table V in the order of increasing values of unit air infiltration rate per ft of crack length of doors and openable windows. The unit air infiltration rate ranged from 15 to 45 cu ft/hr(ft) to crack length for the selected conditions of 10 mph wind and indoor-outdoor temperature difference of 40 F. The lower end of the range of values based on observed data is comparable with values published in the ASHRAE Guide[5] for weatherstripped double-hung metal or wood sash windows at the same wind velocity, whereas the upper end of the range of these values is comparable with the published value for a non-weatherstripped double-hung metal window and higher than the published value for a residential casement window with 1/32-in. cracks, at the same wind velocity. These comparisons are not entirely valid because the data published in the ASHRAE Guide[5] do not take into account the effect of temperature difference on air infiltration.

Table V Relation of Air Infiltration Rate to Crack Length

House	Unit Air Infil-tration Rate cu ft/hr (ft)	Adjusted Air Change Rate hr^{-1}	Building Volume per Unit Crack Length ft^3/ft	No. of Stories	Age of Building yrs.	Foundation Type	Wall Material
F	15	0.37	41	1	New	Basement	Stone Veneer
G	21	0.50	42	1	New	Crawl Space	Frame
A	22	0.62	35	1	20	Crawl Space	Brick Veneer
B	23	0.75	31	1	30	Basement	Frame
D	30	0.99	30	2	20	Basement	Frame
H	30	0.71	42	2	46	Crawl Space	Frame
I	32	0.48	67	2	New	Basement	Brick Veneer
E	36	0.86	42	2	40	Basement	Frame
J	36	0.66	54	1	New	Slab on Ground	Brick Veneer
C	45	0.48	94	1	New	Crawl Space & Basement	Brick Veneer

Examination of Table V does not indicate any significant correlation between the unit air infiltration rate and age of the house or type of wall or foundation construction, but does show that the four 2-story buildings had a higher unit infiltration rate than four of the 1-story buildings and equal or lower infiltration rate than the 1-story houses, J and C. However, the data on door and window crack lengths in Table I indicate that the door cracks constituted a higher percentage of the total crack length in houses J and C than for the other houses. This fact may account for the high unit air infiltration rate of these two 1-story houses, since the cracks around doors are usually greater in width than those around windows. Residence C had the highest unit air infiltration rate and also the highest value of building volume per unit crack length, as shown in Table V. This house had a large volume, but only a few openable windows, which accounts for the high ratio of building volume to crack length. However, it does not account for the high value of unit air infiltration rate.

It should be noted that these comparisons are made between the infiltration through all avenues of leakage in the test houses with the air leakage for windows only as published in the ASHRAE Guide.[5] The field study did not include measurement of the crack width of the windows and doors nor the identification of other sources of leakage such as fireplaces, chimneys, interstices in the wall construction, and penetrations by electrical and plumbing fixtures. Some of these factors may have contributed to the high value of unit air infiltration rate observed for house C.

INFILTRATION BASED ON AIR CHANGE RATE

The procedures described in the ASHRAE Guide[5] for computing air infiltration rates by the air change method were applied to the ten houses tested. Following the usual assumption that the total infiltration volume for a residence is equal to the sum of the infiltration volumes for the individual rooms, the computed air changes per hr by this method ranged from about 0.6 to 1.5. When the observed air change rates in the ten houses were adjusted to the design weather conditions in Indiana by means of Eq. (3), the resulting infiltration rates ranged from about 0.54 to 1.45 air changes per hr, and are in good agreement with the computed values. However, comparisons on a house-by-house basis between observed air change rates, after adjustment by Eq. (3), and the values computed by the Guide[5] procedures revealed numerous inconsistencies. Thus, the reader is cautioned against drawing more detailed conclusions from the data than are warranted.

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