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BY

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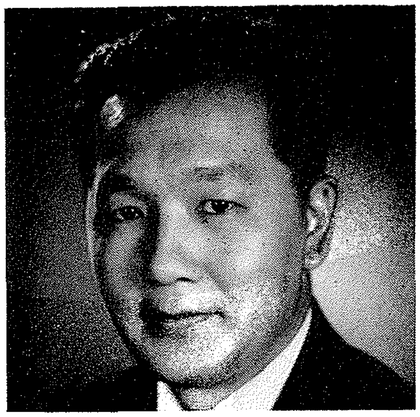

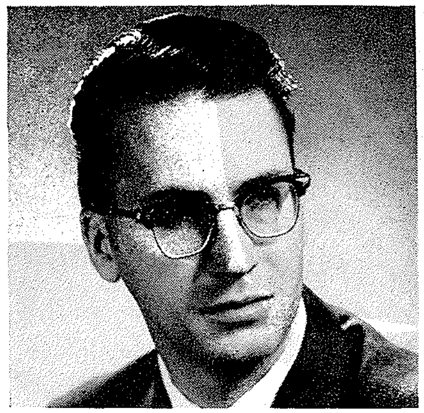

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Air leakage and pressure measurements on two occupied houses

Air leakage is an important item in the heat balance of most houses. It is also the usual source of fresh air and air for combustion. Exfiltrating air is the major means by which moisture is lost from a house during the winter and greatly influences the relative humidity that is maintained; it can also be a major cause of condensation problems if the moisture which it carries is deposited within walls, windows or roof construction. Air leakage measurements using the tracer gas technique[1] were carried out on two occupied one-story houses located in Ottawa, Canada, from the winter of 1960-61, through the summer, to the winter of 1961-62. Similar measurements[2, 3, 4, 5, 6] have been reported recently, but the amount of such information applicable to North American building practice is still quite limited. It is, therefore, desirable to extend the available information on house air leakage characteristics.

In these present studies an attempt was made to relate the measured air leakage to weather conditions and to furnace operation. The measured values are also compared with those calculated by ASHRAE Guide And Data Book procedures. In addition, some measurements were made of the differences in pressure across the walls of the houses and the data related to wind velocity and direction for both summer and winter conditions. These records, together with pressure differences measured across the ceiling, indicate the pattern of air leakage.

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DESCRIPTION OF HOUSES

Both houses were constructed by project builders and are located in built-up areas. Plan views of the two houses are given in Figs. 1 and 2. Both are one-story, five-room houses of insulated wood-frame construction with full basement. Inside finish is plasterboard in house No. 1 and plaster in house No. 2. Attics are vented. Openable windows in house No. 1 are double horizontal sliding sashless units and those in house No. 2 are double-hung vertical sliding units, with storm sash in winter. House No. 2 has louvred openings with hinged, weatherstripped covers beneath fixed double windows in the living-dining room. In both houses basement windows are hinged, with storm sash. Both houses are heated by forced warm-air heating systems with high pressure gun-type oil burners; house No. 2 has a solid-fuel fireplace in the living room. Prior to the summer tests a detached garage was constructed adjacent to the west wall of house No. 2. The plan area, based on inside dimensions, is 830 sq ft for house No. 1 and 1076 sq ft for house No. 2. The net volume, including basement and allowing 10% for furnishings and partitions, is 11,900 cu ft for house No. 1 and 15,300 cu ft for house No. 2.

Distribution of window and door cracks is shown in Table I. Actual crack lengths have been adjusted to give the length equivalent to that of average fit double-hung wood-sash, weatherstripped windows based on the leakage factors in the Table. These factors are consistent in general with those given in the ASHRAE Guide And Data Book, with some adjustments based on judgment. The leakage factor for the sashless windows is an average figure derived from test results for a number of similar units.

In house No. 2 different window arrangements existed during each of the three test periods. Storm sashes were applied to all windows except two in the basement during both winters; during the second winter adhesive tape was applied around the exterior perimeter of all storm sashes on the first floor and to the interior perimeter of all the basement windows. The results of air infiltration calculations by the crack method given in the ASHRAE Guide And Data Book are also shown in Table I for a wind velocity of 10 mph. These are simply values of total air flow through one-half of the total equivalent crack based on a leakage factor of 13 cu ft per ft of crack. The values are expressed in terms of air changes per hr, based on the combined volume of first floor and basement.

METHOD AND INSTRUMENTATION

Ventilation rates were determined from measurements with a katharometer of the rate of change of concentration of helium gas discharged in the house. The relationship between the concentration of the tracer gas and ventilation rate is expressed by:

$$R = \frac{k}{v} = \frac{1}{t_2 - t_1} \ln c_1/c_2 \qquad (1)$$

where

k = infiltration rate
v = volume of enclosure
R = air change rate
c = tracer gas concentration
t = time

The katharometer used was similar to the one designed by the National Bureau of Standards[7]. A continuous sample of helium-air mixture was drawn with a small diaphragm pump through a drying bottle containing calcium chloride and then to the katharometer. The imbalance of the katharometer bridge circuit caused by the changes in the helium concentration was recorded on a millivolt recorder.

In the house trials, helium was injected into the supply plenum of the forced warm-air heating system. The circulating blower operated continuously during each test. A sample of helium-air mixture was drawn from the return air plenum to the katharometer, the output of which was recorded. Air circulation rates provided by the furnaces were equivalent to about six air changes per hr, which were large in relation to the rates of air infiltration measured.

Doors to all rooms and basement were open and it is assumed, therefore, that a fairly uniform concentration of helium was obtained in the houses throughout each test and that the concentration in the return plenum was a properly weighted average of the whole house concentration. Circulation of air by the furnace blower did not influence air infiltration as no significant pressure difference between rooms was possible with all spaces freely interconnected.

To measure the pressure differences across the exterior walls of house No. 1, pressure taps of ¼-in. copper tubing were mounted flush with the outside surface of the walls, 4 ft above the first floor level. These were

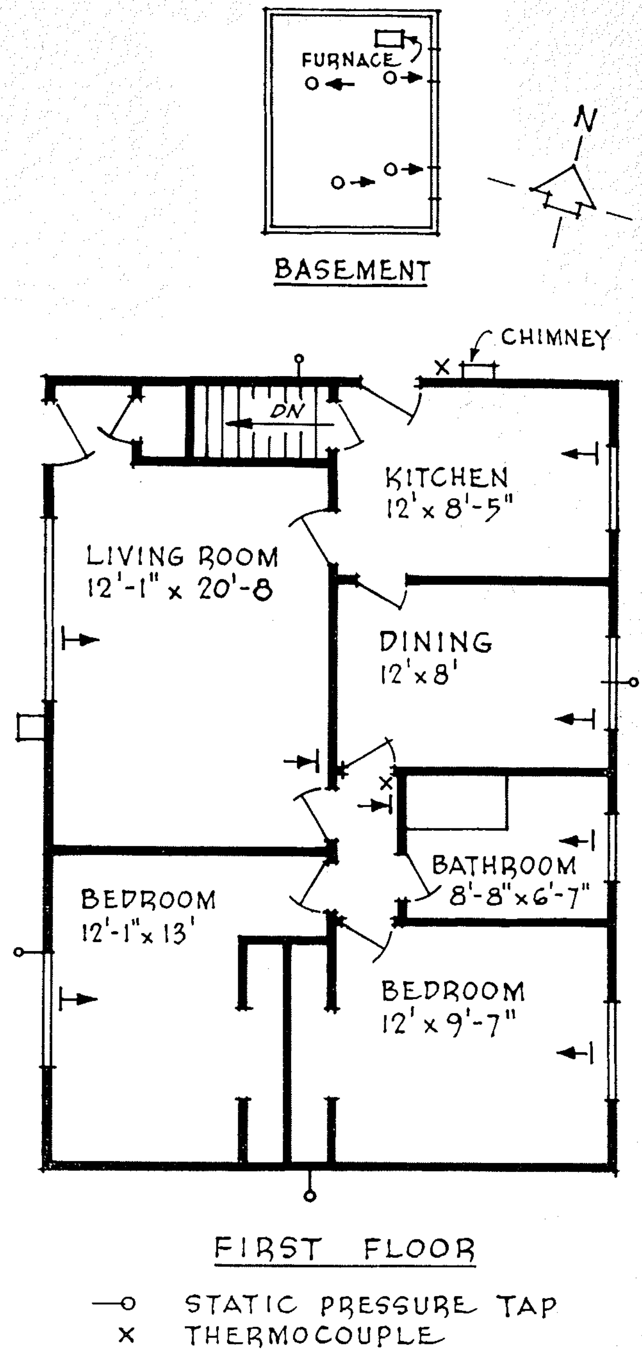


Fig. 1 House No. 1

connected through the window frames at the same level to plastics tubing which was brought to a central location in the basement. Pressure taps were also installed to measure the pressure difference across the ceiling and chimney draft. A cup anemometer was located 25 ft from ground level above one side of the house to record wind speed and direction. House No. 2 was similarly instrumented, but the height of the pressure taps through exterior walls varied from 2 to 5 ft above the first floor level and the anemometer was located 24 ft from the ground and 30 ft to the rear of the house.

The pressures were measured with a diaphragm, strain-gauge-type, pressure transducer. The voltage output from the pressure transducer was recorded on a 16-point millivolt recorder. Plastics tubing from each pressure tap was connected to a 12-point pressure

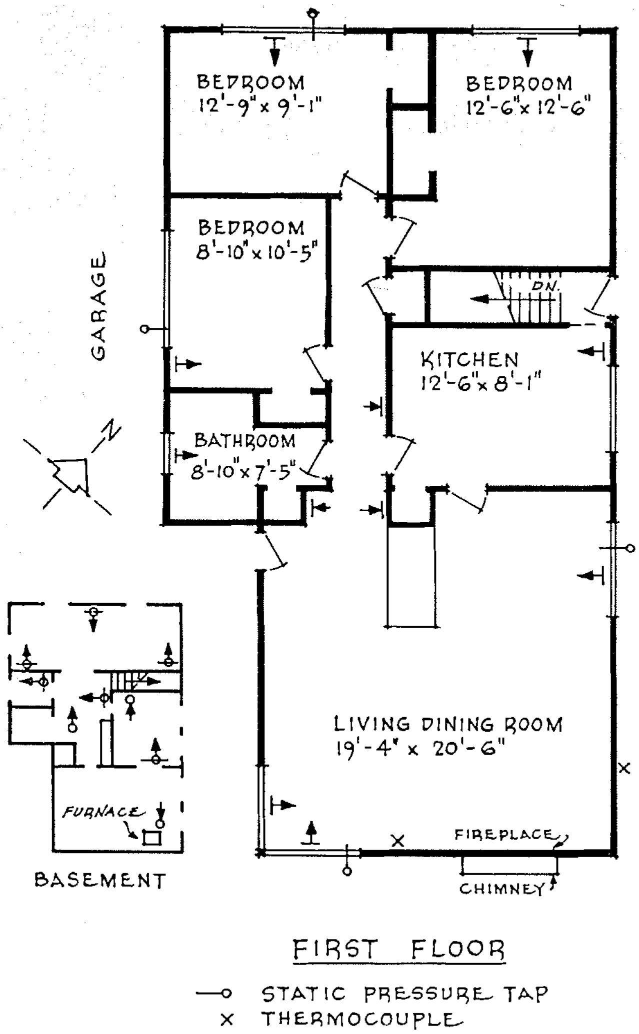


Fig. 2 House No. 2

switch controlled by a selector switch in the millivolt recorder. Two wind speed readings were recorded during a recorder cycle with each reading representing the integrated wind speed over one-half the recorder cycle. The time interval for each recorder cycle was 3.84 min.

Because of the probability of a zero shift in the pressure transducer, the zero pressure difference output and the output with the calibration resistor in the transducer bridge circuit were also recorded during each cycle. A shaft encoder was attached to the slide wire shaft of the millivolt recorder which, in conjunction with a punched paper tape recorder and its attendant control unit, gave all records in three digit binary form on a punched paper tape. The paper tape was processed through a digital computer to obtain the actual pressure and wind speed readings.

All wind velocities referred to in this paper are those measured on site, approximately 25 ft above ground. The wind speed is affected both by the height at which it is measured and the surrounding terrain. Both houses are located in residential districts. House No. 1 is located at the edge of a housing area with its south wall facing a wooded region. The records of the average hourly wind speed obtained at the two houses were compared with those recorded at the Uplands Airport with an anemometer 25 ft above ground. The airport is located in a flat open area, 6 miles southwest of house No. 1 and 5 miles southwest of house No. 2. The ratio of the wind velocity at the houses to that at the airport averaged 0.65 for house No. 1 and 0.56 for house No. 2 over a wide range of wind conditions.

AIR LEAKAGE TEST RESULTS

Results of the air leakage tests conducted in both houses are given in Tables II and III. The hourly air change rates quoted are based on the net volume of the houses including the basement. During the two winters, measured ventilation rates for house No. 1 varied from 0.25 to 0.41 air changes per hr; this compares with rates of 0.37 to 0.63 air changes for house No. 2 during the first winter, and 0.33 to 0.57 air changes during the second winter with the openable windows taped. During the summer, measured air change rates varied from 0.07 to 0.16 for house No. 1 and 0.11 to 0.23 for house No. 2.

Figs. 3 and 4 show the relationship between ventilation rate and wind speed for both houses for the summer condition. Assuming a flow exponent of ½

Table I Equivalent Crack Length and Calculated Air Leakage

House No. 1

	Length of crack, ft			
	N	S	E	W
First floor	38.7	—	126.0	155.9
Basement ...			32.6	
	38.7		158.6	155.9

Overall Total—353.2 ft

Total crack length to net volume ratio—0.030 ft/ft³

House No. 2 (winter storm sash on openable window)

	Length of crack, ft			
	N	S	E	W
First floor	73.3	24.3	92.0	109.3
Basement ...	34.0		85.0	51.0
	107.3	24.3	177.0	160.3

Overall Total—468.9 ft

Total crack length to net volume ratio—0.031 ft/ft³

Overall total crack length for house No. 2 as above with windows taped is 313.0 ft and with no storm-sash on openable window (summer window arrangement) is 567.3 ft.

Air Change Rates

House No. 1 0.20 air change per hr

House No. 2

a—storm sash on openable window —0.20 air change per hr

b—as above with windows taped —0.13 air change per hr

c—storm sash removed —0.24 air change per hr

Notes: 1. Equivalent crack length given in terms of corresponding length of average double-hung wood-sash weatherstripped window with assumed air leakage of 60 cfh per ft at a pressure difference of 0.3 in. of water (equivalent to 25 mph velocity head). Other air leakage values assumed as follows:

	cfh
Average double-hung wood sash window	—100
As above with storm sash	— 60
As above with storm sash taped	— 45
Casement window with storm sash	—120
As above with window taped	— 45
Double horizontal sliding sashless window	—120
Fixed window	— 30
Weatherstripped door with storm door	—120

2. Air change rates based on wind speed of 10 mph and one-half total equivalent crack length.

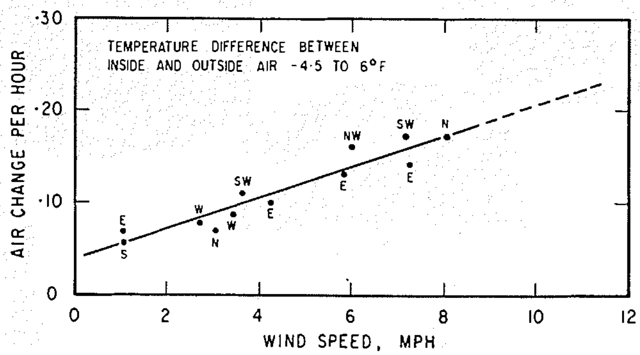


Fig. 3 Ventilation rate, wind speed for House No. 1

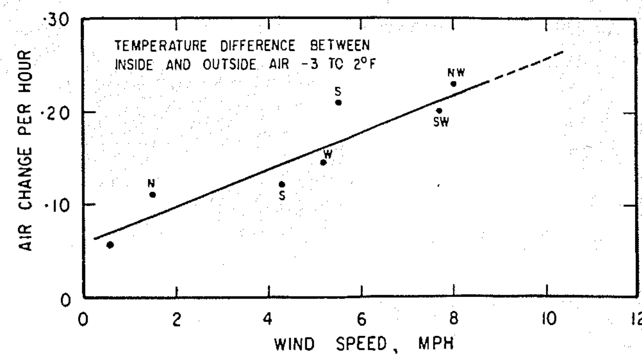


Fig. 4 Ventilation rate, wind speed for House No. 2

for the cracks in the enclosure, a linear relationship is obtained. The increase in air change rate for each mph of wind is 0.017 for house No. 1 and 0.020 for house No. 2. No effect of wind direction is evident from the limited records. As observed by others[2] an apparent ventilation rate was obtained with no wind and only small temperature differences. This amounted to 0.04 and 0.06 air changes per hr for houses 1 and 2, respectively. It is thought that this was due in part to the small temperature differences that occurred during most tests as well as to loss of helium by diffusion through cracks in walls and ceiling.

In Fig. 5 the ventilation rates obtained for house No. 1 during calm periods with the furnace off are plotted against the square root of the temperature difference in order to indicate the influence of house stack effect. The air leakage increased by 0.024 air changes per hr for each increment in the square root of the temperature difference. Inside to outside temperature differences in these tests did not exceed 35 F, so that the temperature rise in the chimney flue due to prior furnace operation would be small. Figs. 3 and 5 have been combined in Fig. 6 to compare the effect on ventilation rate of wind and house stack effect with each acting independently. For example, an inside-to-outside temperature difference of 38 F induces the same total rate of air change as that due to wind at 8 mph. Insufficient data prohibited such comparison for house 2.

Table II Results of Infiltration Tests; House No. 1

Test No.	Date	Temperature, F indoor	Temperature, F outdoor	Temperature Difference, F	Average Wind Velocity, mph	Wind Direction	Furnace Cycle	Infiltration Rate, Air Change/hr
Winter Test								
1	2.2.61	75	0	75	.5	W	off-on	.36
2	3.2.61	74	10	64	8.6	NE	off-on	.41
3	7.2.61	75	22	53	3.1	S	off	.22
4	8.2.61	75	37	38	3.9	SW	on	.23
5	9.2.61	70	38	32	7.7	SW	off	.24
6	10.2.61	72	30	42	8.3	N	on-off	.25
7	13.2.61	70	25	45	9.6	NE	off	.25
8	14.2.61	77	42	35	7.2	SW	on-off	.16[1]
Summer Test								
9	1.8.61	75	72	3	3	N	off	.07
10	2.8.61	71.5	75	—4.5	4.2	E	off	.10
11	3.8.61	74	76	—2	6	NW	off	.16
12	4.8.61	77	79	—2	1	E	off	.07
13	10.8.61	80	86	—6	7.1	SW	off	.17
14	14.8.61	70	68	2	3.4	W	off	.09
15	16.8.61	69	63	6	8	N	off	.17
16	17.8.61	69	71	—2	2.7	W	off	.08
17	18.8.61	71	74	—3	3.6	SW	off	.11
18	21.8.61	71	65	6	7.2	E	off	.14
19	22.8.61	71	68	3	1	S	off	.06
20	23.8.61	76	73	3	5.8	E	off	.13
Winter-Spring Test								
21	6.3.62	68	33.5	34.5	12	NE	off	.28
22	7.3.62	70	34.5	35.5	6	E	off	.22
23	8.3.62	72	38	34	1	E	off	.18
24	9.3.62	68	38	30	6	NE	off	.18
25	13.3.62	68	34.5	33.5	9	E	off	.23
26	14.3.62	69	40	29	6.3	SW	off	.20
27	15.3.62	71	41	30	11	W	off	.25
28	16.3.62	70.5	41.5	29	7.6	W	off	.18
29	19.3.62	72	38.5	33.5	2.6	E	off	.15
30	6.4.62	66	37	29	0	—	off	.125
31	19.4.62	68	49	19	2.1	—	off	.125
32	6.5.62	70	54	16	2.8	E	off	.13

[1] barometric damper sealed

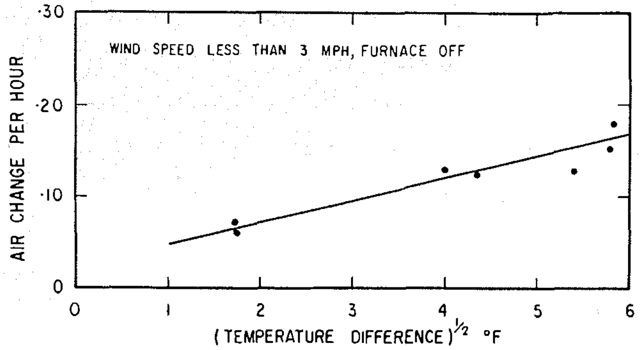


Fig. 5 Ventilation rates, House No. 1, with furnace off in calm period

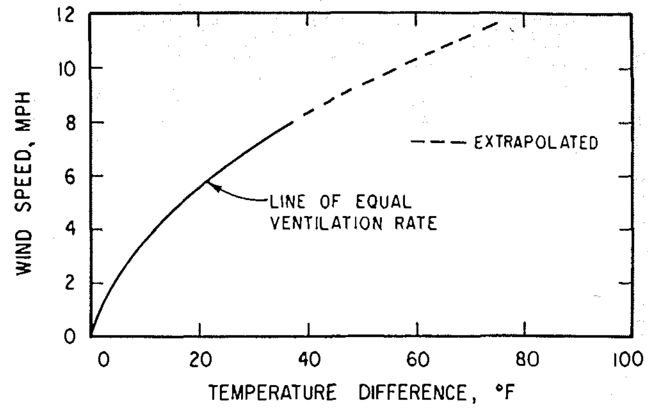


Fig. 6 Figs. 3 and 5 combined

The combined effect of wind speed and temperature difference for house No. 1 is shown in Fig. 7. Ventilation rates obtained during periods with inside-to-outside air temperature differences of 29 to 35 F and with the furnace off are plotted against the wind speed. The intersection with the Y-axis is based on Fig. 5 and indicates a ventilation rate for stack effect alone, at this temperature difference, of 0.16 air changes per hr. From the curve for the summer test, reproduced from Fig. 3, this air change would be induced by wind effect alone at 7.5 mph. The combined wind and stack effect at this wind velocity is 0.21 air changes, or 0.65 of the sum of the ventilation rates due to wind and stack effect acting independently.

In establishing the curve of air change rate for a temperature difference of 70 F, it was assumed that this ratio of 0.65 is constant for house No. 1 for any combination of wind and temperature difference in Fig. 6. This assumption would appear to be valid, provided that the exponents of flow for the various cracks and openings in the building remain constant, since the pattern of air flow will be similar for all such conditions. It is seen in Fig. 6 that a temperature difference of 70 F is equivalent to a wind velocity of 11.2 mph. In Fig. 7 the air change rate at these combined conditions is 65% of the sum of the separate wind and temperature effects; the intersection with the Y-axis is obtained by extrapolating Fig. 5. At the higher wind speeds the effect

Table III Results of Infiltration Tests; House No. 2

Test No.	Date	Temperature, F indoor	Temperature, F outdoor	Temperature Difference, F	Average Wind Velocity, mph	Wind Direction	Furnace Cycle	Infiltration Rate, Air Change/hr
Winter-Spring Test								
1	9.3.61	70	24	46	2.9	NE	—	.37
2	14.3.61	70	25	45	10.2	NE	on-off	.63
3	15.3.61	70	44	26	2.7	SW	off	.42
4	16.3.61	73	25	48	7.1	NW	on-off	.49
5	17.3.61	75	15	60	10.4	NW	on-off-on	.55
6	20.3.61	73	32	41	2.5	NW	off	.39
7	21.3.61	74	44	30	5.9	NE	off	.50
8	23.3.61	72	40	32	4.3	NE	off-on-off	.40
9	24.3.61	71	46	25	0	—	off	.24[1]
10	29.3.61	73	40	33	6	SW	off	.39
11	30.3.61	74	35	39	9.1	NW	off	.45
12	19.4.61	73	55	18	5.5	NE	off	.59[2]
13	20.4.61	71	65	6	4.2	SW	off	.25
Summer Test								
14	30.6.61	75	75	0	8	NW	off	.23
15	4.7.61	71	74	—3	7.7	SW	off	.20
16	5.7.61	69	71	—2	4.3	S	off	.12
17	6.7.61	71	69	2	5.2	W	off	.145
18	7.7.61	71	70	2	1.5	N	off	.11
19	10.7.61	70	70	0	.5	—	off	.06
20	11.7.61	74	77	—3	5.5	S	off	.21[1]
Winter Test—Window Sealed								
21	3.1.62	71	25	46	9.4	SW	on-off-on	.49
22	4.1.62	71	0	71	2.4	NW	off-on-off	.39
23	5.1.62	76	5	71	6.3	NE	on-off-on	.57
24	8.1.62	73	35	38	10.2	SW	off-on-off	.42
25	9.1.62	71	25	46	10.4	SW	on-off-on	.45
26	10.1.62	71	12	59	10.5	SW	off-on-off	.46
27	12.1.62	70	22	48	5	S	off-on-off	.45
28	15.1.62	70	33	37	.5	—	off-on-off	.33
29	17.1.62	71	5	66	11.5	W	off-on-off	.46
30	19.1.62	74	15	59	1.1	—	off-on-off	.45

[1] barometric damper sealed [2] fireplace damper open

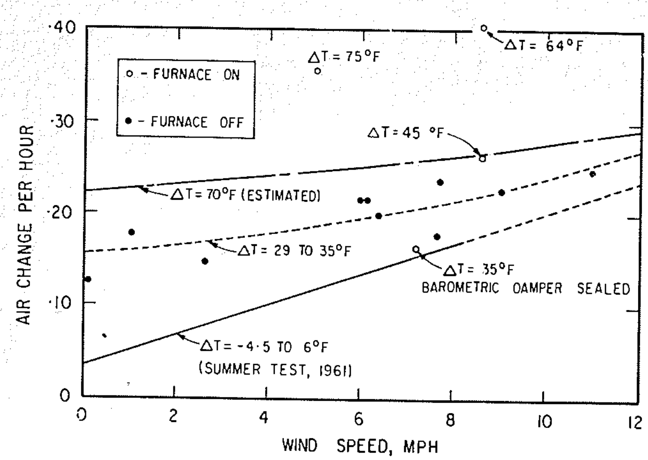


Fig. 7 Ventilation rate, combined wind and temperature effects for House No. 1

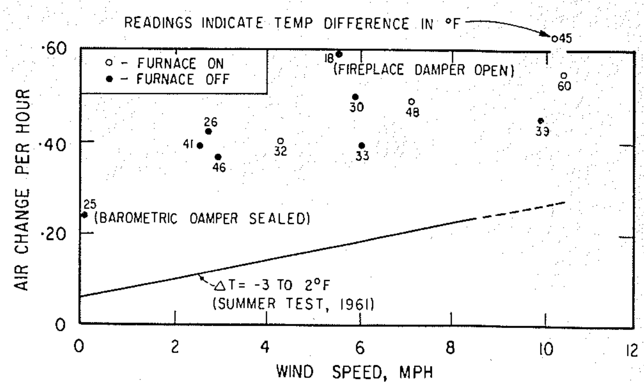


Fig. 8 Ventilation test results for House No. 2, the winter of 1960-61

of combined wind and temperature difference approaches that due to wind alone.

The ventilation rate during cold weather is affected by the additional air flow up the flue induced by furnace operation. Two air leakage values obtained with air temperature differences of 64 and 75 F and with the furnace in operation are shown in Fig. 7. These two values are well above the estimated curve for an air temperature difference of 70 F. To determine the amount of air flow through the chimney due to furnace operation, the carbon dioxide concentration was measured with an Orsat gas analyzer in the smoke pipe between the furnace and barometric damper and inside the chimney just above the smoke pipe inlet on a number of occasions with the furnace in operation.

The furnace at the time of the tests was equipped with a 0.50 gph nozzle burning No. 2 fuel oil and was operating with a Bacharach smoke No. 2. At an inside to outside temperature difference of 75 F and a wind speed of 5 mph the air flow, based on the CO_2 measurements, was about 1300 cu ft per hr or 0.11 house air changes per hr through the furnace, which was increased by the diluent air through the barometric damper to a total of about 4800 cu ft per hr or 0.40 air changes per hr.

The ventilation rates obtained during the cold weather and with the furnace on are close to this value; this suggests that with the furnace in operation air flow out of the house took place largely through the chimney. The ventilation rate obtained with the barometric damper sealed indicated an appreciable reduction in air leakage.

The results of the ventilation tests on house No. 2 for the winter of 1960-61 are shown in Fig. 8 and those for the winter of 1961-62 with the windows taped are shown in Fig. 9, together with the curve for the summer tests in both instances. It should be remembered that the equivalent crack length of the summer tests was somewhat greater than for either winter due to the removal of storm sash. The slope of the curve of air leakage for the summer tests therefore is greater than is appropriate for the window arrangement of either winter, particularly the second.

Insufficient information is available to establish curves for specific values of temperature difference. The air leakage values for the first winter, however, are significantly higher than the summer values due to wind effect alone, even at the highest wind speeds. Stack effect has a much greater influence on the ventilation rate for house No. 2 than for house No. 1, due probably to differences in the vertical distribution of cracks. The air change rates for the second winter are somewhat lower than those of the first, especially at the higher wind speeds. Air leakage appears to be less influenced by wind and to be primarily a function of furnace operation and stack effect.

Some increase in air leakage due to furnace operation is evident on close scrutiny of the results in Fig. 8, although it would appear to be somewhat less than for house No. 1. Opening of the fireplace damper caused a significant increase in air leakage; sealing of the barometric damper caused a significant decrease, even with the furnace off. The furnace was operating during all of the tests the results of which are shown in Fig. 9. Measurements of CO_2 concentration in the flue gas during the second winter indicated air flows corresponding to 0.13 air changes per hr through the furnace and a total of 0.38 air changes per hr out the chimney with the furnace operating steadily, with an inside to outside temperature difference of about 40 F and a wind of about 10 mph. Thus, with the furnace on a large proportion of the air flow out of the house occurred through the chimney.

PRESSURE MEASUREMENTS

To obtain a relationship between pressure difference across the walls of the houses and the wind speed, the following second equation was assumed:

$$P = A + C V^2 \qquad (2)$$

where

P = pressure difference, in. of water
V = wind speed, mph
A = constant
C = constant

The pressure difference and the wind speed readings recorded on punched paper tape were processed through a digital computer to determine the best fitting curve using the method of least squares. Fig. 10 is a typical plot of the pressure difference across a windward wall vs wind velocity. The wind speed recorded was the average wind speed during a half recorder cycle (1.92 min), whereas the pressure readings were instantaneous

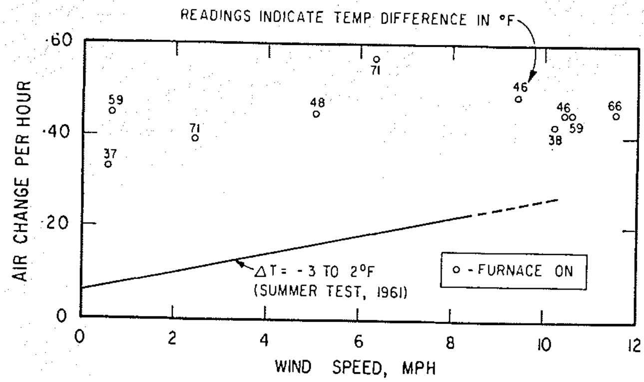


Fig. 9 Ventilation test results for House No. 2, the winter of 1961-62, taped windows

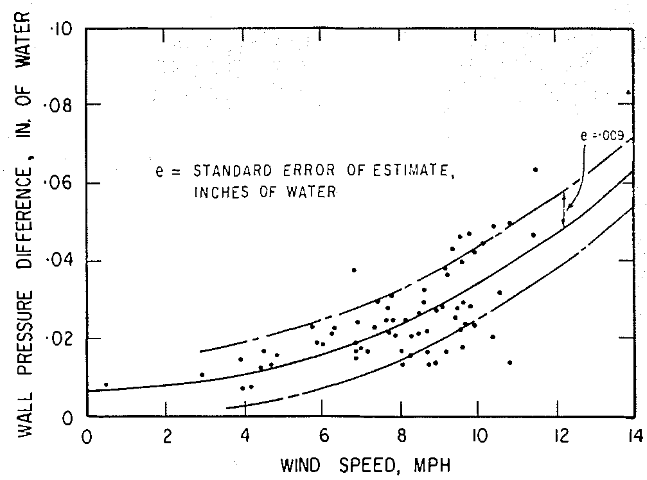


Fig. 10 Typical pressure plot of pressure difference on windward wall vs. wind velocity

measurements. Because of the fluctuations in wind speed and direction, considerable scatter of the results occurs; it is more pronounced at higher wind speeds. The extent of scatter is indicated by the standard error of estimate.

Pressure difference vs wind speed relationships for all four walls of house No. 1 are shown in Figs. 11 and 12 for summer and winter conditions, with wind from the east. Similar results for house No. 2 are shown in Figs. 13 and 14 with wind from the northwest. The pressure difference corresponding to one velocity head is also shown. The windward wall is at the rear in both cases. The results for the summer condition are similar for both residences, with infiltration through windward and exfiltration through leeward walls.

Pressure differences across side walls can be positive or negative, depending on small changes in wind direction. The pressure difference across the windward wall is 86% of the total pressure difference from windward to leeward sides for house No. 1 and 83% for house No. 2. To balance the air flow, some exfiltration must take place through ceiling construction and chimneys. Extensive measurements of draft at the base of the chimneys during the summer tests indicated that draft generally increased with wind velocity for all wind directions in house No. 2 and for all but a southwest wind in house No. 1. At lower wind speeds the draft sometimes exceeded one velocity head.

The results for the winter conditions in Figs. 12 and 14 indicate the influence on pressure differences of house stack effect and furnace operation. No distinction is made between furnace-off and furnace-on conditions, the results indicating the net effect of this and other factors during the test period.

With wind at 10 mph the pressure difference across the windward wall was greater than that for the summer conditions by 44% for house No. 1 and by 66% for house No. 2; information for house No. 2 is for a somewhat higher temperature difference than for house No. 1. The magnitude and direction of pressure differences across the walls approximately parallel to the wind would

Fig. 11 House No. 1, summer

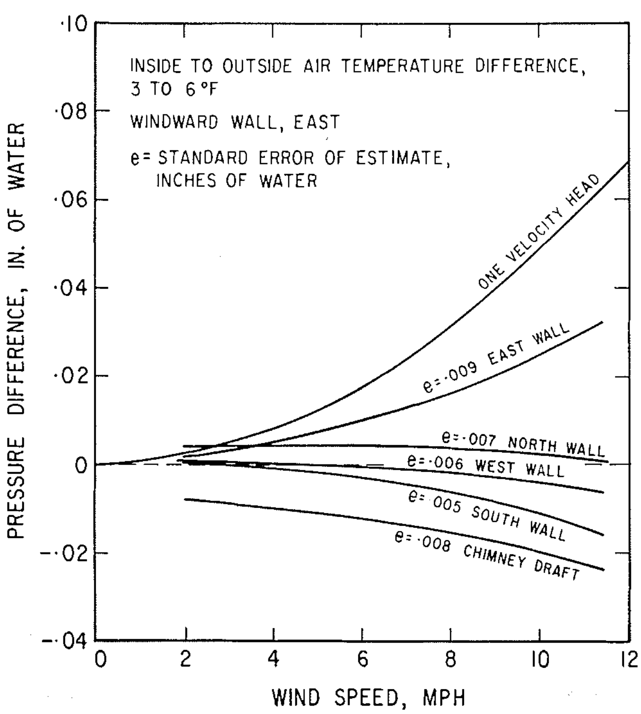
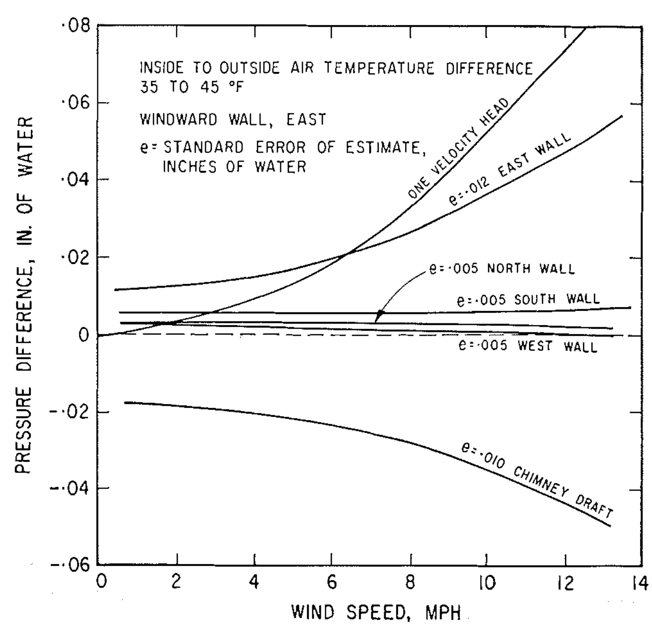


Fig. 12 House No. 1, winter



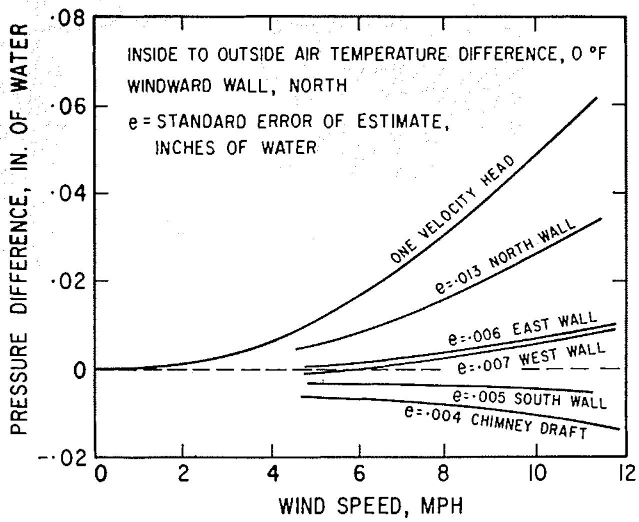


Fig. 13 House No. 2, summer

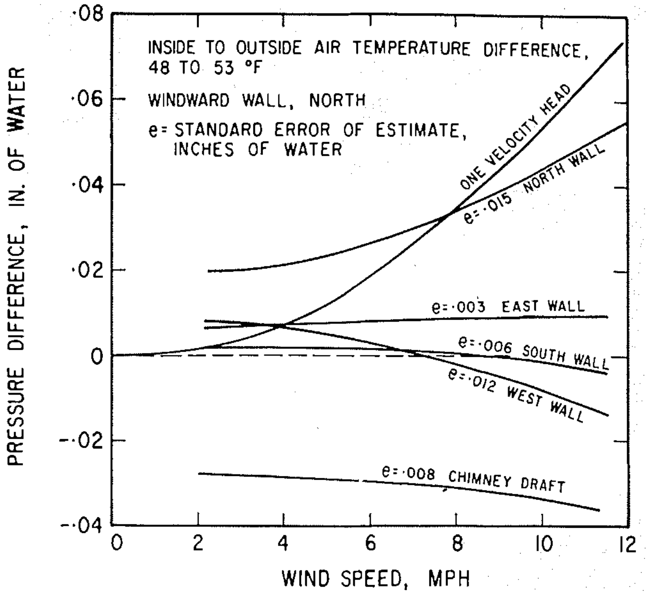


Fig. 14 House No. 2, winter

again appear to be sensitive to small changes in wind direction.

Under the winter condition, however, infiltration occurred through all walls of house No. 1 at wind speeds up to 12 mph; infiltration occurred through all walls of house No. 2 at wind speeds up to 7 mph. At lower wind velocities it must be assumed that all of the exfiltration took place through the chimney and ceiling construction. The results indicate an increase in chimney draft to wind action.

Analysis of the pressure differences measured across the ceiling of both houses indicates that they are generally independent of wind velocity and are relatively small. During the summer the pressure differences ranged between plus and minus 0.002 in. of water for both houses. In the winter, with the furnace off, the pressure inside each house was higher than in the attic.

With inside-to-outside temperature differences of 47 F for house No. 1 and 65 F for house No. 2, this pressure difference was generally 0.005 in. of water, or less. With the furnace in operation the attic pressure was positive with respect to inside in house No. 1, generally by 0.005 in. of water, or less, at a temperature difference of 47 F indicating a reversal of the direction of air flow. Under this condition exfiltration occurred mainly through the chimney. In house No. 2 the pressure difference across the ceiling did not appear to be greatly influenced by furnace operation during either winter.

To estimate the neutral pressure level for the two houses the average of the pressure difference across the four walls was determined at a number of outdoor temperature conditions at wind speeds of less than 4 mph. This is equivalent to determining the value of the "constant" A of Eq. (2) for the different temperature conditions. The results for both houses are shown in Fig. 15. No distinction was made between furnace-on and furnace-off conditions, which may account for some of the scatter in the points.

From Fig. 15, the neutral pressure level is estimated to be 10 in. above the first floor ceiling level in house No. 1 and 1 ft 4 in. below the first floor ceiling level in house No. 2. It has already been noted that, in house No. 1, the pressure difference between house and attic was positive with the furnace off and negative with the furnace on. At an inside-to-outside temperature difference of 65 F, this change in pressure difference corresponded to a change in the neutral pressure level of about 2 ft. Some further information on neutral zone levels for house No. 2 has already been reported.[8]

SUMMARY

Detailed results of air leakage and pressure distribution measurements have been presented for two single-story houses with oil-fired warm air furnaces. The houses had similar ratios of equivalent window and door crack length to total volume but house No. 2 had a greater proportion of crack at ground level. The results, although specific to the test houses, have implications relative to other similar buildings.

During the summer, air leakage rates of both houses varied approximately linearly with wind velocity. During the winter, the pattern and extent of air leakage were influenced by both house stack action and furnace operation. The influence of house stack action alone, independent of the effects of wind and furnace operation, was determined for house No. 1 and the air change rate found to vary linearly with the square root of the inside-to-outside temperature difference.

The air change rate under the combined influence of wind and temperature difference was less than the sum of rates due to wind and temperature acting independently. This is at variance with other investigators[2, 5] who have assumed that wind and temperature effects are independent and additive. At the higher wind velocities and with the furnace off, the ventilation rate in house No. 1 due to combined wind and stack effects was only slightly above that induced by wind action alone. House No. 2 exhibited a greater stack effect, presumably due to the greater amount of crack at lower levels.

The influence of furnace operation on air leakage was quite marked. In house No. 1, ventilation rates with the burner on were up to 50% greater than with the burner off and corresponded closely with measured rates of air flow up the chimney. Exfiltration occurred

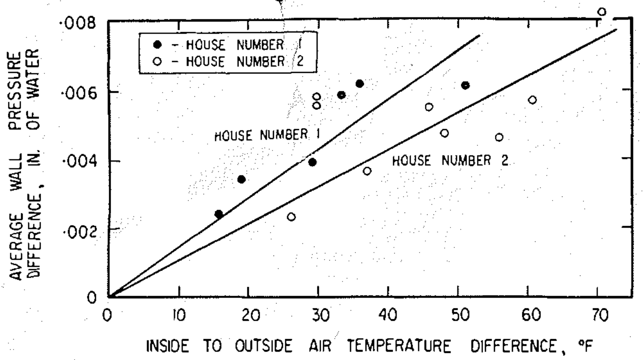


Fig. 15 Average pressure difference across walls due to temperature effect for both houses

across the ceiling construction with the furnace off and infiltration with the furnace on. In house No. 2 the effect of furnace operation was not so marked until the windows were taped; then air leakage rates with the burner on were relatively insensitive to wind and outside temperature and a large proportion of the exfiltration took place through the chimney. Some exfiltration occurred through the ceiling construction even with the furnace on.

The ASHRAE Guide And Data Book crack method of calculating air leakage considers only wind action and assumes, in effect, that 64% of the velocity head of the wind acts across the cracks. For houses it is common to base the calculation on the total crack. For larger open buildings the ASHRAE Guide And Data Book recommends using not less than half of the total crack. Any comparison of calculated air leakage values and actual values is arbitrary, since it depends on the selection of air leakage coefficients and amount of crack in the calculation and on the definition of wind velocity in the measurements.

Calculated air change rates for wind at 10 mph based on one-half the total crack are in good agreement with measured air change rates during the summer with wind at 10 mph as determined on site. This would appear to be due mainly to a fortuitous selection of leakage coefficients. With infiltration primarily through one windward wall, the pressure difference across the wall was equivalent to about 50% of the velocity head of on-site wind. The measured values obtained at 10 mph during the winter are greater than calculated values by an amount depending upon the temperature difference between inside and outside and on furnace action.

With the burner operating, actual values are two or more times those calculated. The discrepancy is greatest with house No. 2 which exhibited the greater stack effect. Calculated air leakages based on the total crack length are considerably in excess of measured values for the summer; for the winter the calculated values agree well with measured values for house No. 1 with the furnace on, but are somewhat lower than measured values for house No. 2. Air leakage test results, augmented by pressure difference measurements, are required on a variety of house types to develop improved calculation procedures.

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