No. 1615

MEASUREMENT OF INFILTRATION IN TWO RESIDENCES

Part II: Comparison of Variables Affecting Infiltration

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INFILTRATION measured in the I=B=R Research Home and Warm Air Heating Research Residence No. 2 by the helium tracer gas method and the weather conditions under which the measurements were made were presented[1] in Part I of this paper. The Research Home was a 2-story brick veneer house with full basement, located on a typical city site surrounded by houses and trees. Research Residence No. 2 was a single-story frame structure with full basement, and located on an open site typical of many new housing developments. Differences in location and construction of the 2 houses caused several noticeable differences in the results of the 2 investigations. The objective of this part of the paper is to compare the effects of the variables related to infiltration in the individual houses and to compare the results for the 2 houses.

Since the measured data were obtained over a range of combinations of wind velocity and direction, and indoor-outdoor temperature difference, and since only a limited number of tests were conducted in each house, it was deemed advisable to correct the measured data to specific conditions of wind and temperature difference. The corrections to the original data were determined from the slopes of plots of the original data assuming in all cases that a straight-line relationship existed between the dependent and independent variables. For example, the average increase in infiltration with each mph increase of wind velocity was ob-

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[1] Exponent numerals refer to References.
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tained from a plot of air change rate as a function of wind velocity. This incremental change was used to correct the measured air change rates to conditions of 0, 7.5 and 15.0 mph winds. The corrected air change rates were plotted as a function of indoor-outdoor temperature difference and the new curves of air change *vs.* temperature difference were used to obtain correction factors for temperature difference. The corrections were repeated twice to obtain the second approximation. Although an inspection of the data for the 2 houses shows that wind direction had some effect on the results, it was not possible to draw conclusions from the data and no corrections were made for wind direction. Unless otherwise noted,

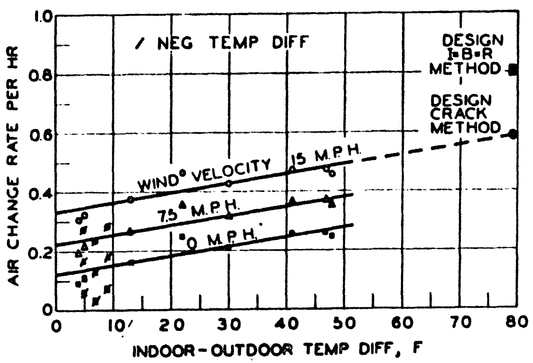

FIG. 1—EFFECT OF TEMPERATURE DIFFERENCE ON FIRST- AND SECOND-STORY AIR CHANGE RATE IN THE I=B=R RESEARCH HOME

the data have been corrected by the foregoing procedure to separate the effects of wind velocity and temperature difference.

RESULTS IN I=B=R RESEARCH HOME

The house air change rate is shown in Fig. 1 as a function of indoor-outdoor temperature difference corrected by 2 approximations for 0, 7.5 and 15 mph wind. The scattering of points is due partly to the wind data, which was taken from the University Weather Station and measured above the roof level where no trees or buildings obstructed it.

Wind velocity affected the infiltration as shown in Fig. 2. Infiltration rate increased with an increase in wind velocity. Wind direction may have an effect on infiltration provided there is unequal crackage on various sides of a building. In the Research Home it was not possible to correlate wind direction and infiltration. It can be seen from Figs. 1 and 2 that a change of 4 deg F in the temperature difference was equivalent to about a 1 mph change in wind velocity. Wind velocity had a special effect on the Research Home by increasing air flow up the chimney; this will be discussed later.

All points used in constructing the curves of Figs. 1 and 2 were obtained when the indoor temperature exceeded the outdoor temperature. Points with slashes

represent a negative temperature difference and were not considered in drawing the curves. They indicate that the summer infiltration rate for a given temperature difference and wind velocity was lower than that for winter. This discrepancy can be explained by the effect of the chimney on increasing the house air change rate during the winter, as discussed later, and the additional shielding during the summer of leaves on the trees surrounding the Research Home.

When infiltration rate is estimated it is common practice to assume that no air passes through properly sealed wall construction. Infiltration rates for the Research Home, as calculated by the *crack* and *air change* methods, are shown in Figs.

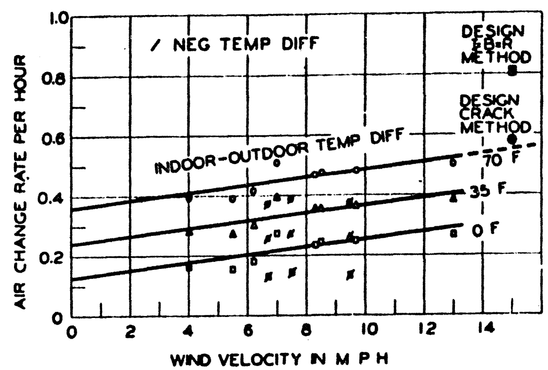

FIG. 2—EFFECT OF WIND VELOCITY ON FIRST- AND SECOND-STORY AIR CHANGE RATE IN THE I=B=R RESEARCH HOME

1 and 2. The crack width for windows and doors was estimated from material in THE GUIDE[2] 1956. The crack was assumed to be 0.04 in. for the weatherstripped windows and 0.09 in. for weatherstripped doors. For these calculations it was assumed that there was no air change between the house and attic and the house and basement. It is interesting to note that the infiltration rate estimated by the *crack* method and the *air change* method fall into good agreement with the test data. However, this is coincidental since the design value was based on wind velocity and did not consider temperature difference.

When investigating infiltration rates it is helpful to consider the neutral zone or plane. The neutral zone is that elevation in a building where the pressure indoors is equal to that outdoors when the building is exposed only to an indoor-outdoor temperature difference. Air flows into the building below the neutral zone and out above it when the temperature indoors is greater than that outdoors. The flow pattern is reversed when the outdoor temperature exceeds the indoor temperature. In the Research Home the neutral zone was calculated to be 100 in. above the first-story floor level. To make this calculation is was assumed that there was no air change between the attic or basement and first and second stories, and that there was no air flow through the exposed walls. In order to determine the approximate location of the neutral zone, the measured indoor-outdoor pressure difference at several locations was plotted against elevation (Fig. 3). A negative pressure difference indicates that the indoor pressure was less than that outdoors. The letters beside each point indicate the exposure where the total pressure was measured. There may be a different neutral zone for each exposure when a wind is blowing, but Fig. 3 gives a mean neutral zone since the curve was drawn taking

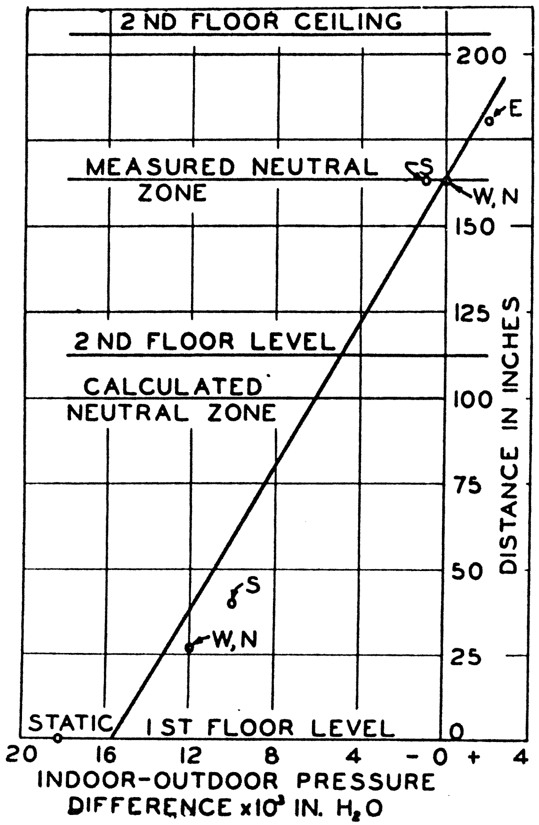

FIG. 3—LOCATION OF THE NEUTRAL ZONE AS DETERMINED BY THE INDOOR-OUTDOOR PRESSURE DIFFERENCE AT VARIOUS ELEVATIONS IN THE I=B=R RESEARCH HOME WITH SOUTH WIND AT 4 MPH, FEBRUARY 10, 1956

all points into consideration. A straight-line relation was assumed; however, this did not introduce a large error because the zero pressure difference usually occurred near the second-story pressure measuring level.

The indicated location of the neutral zone is shown in Fig. 4 as a function of the indoor-outdoor static pressure difference at the first-story floor level. The height of the neutral zone above the first-story floor increased with increased pressure difference, and the measured height of the neutral zone was always greater than

that estimated from the crackage on the 2 floors. The difference in the estimated and measured neutral zone locations might be attributed to leakage through the second-story ceiling not considered in the calculation of the neutral zone location. However, if the ceiling did cause the difference, the neutral zone location should have occurred at some fixed point above the estimated location since the resistance to flow would be constant. Since the height of the neutral zone location varied during the tests another cause of the variation was suggested. The difference was attributed to the effect of the heating plant chimney.

In cold weather the chimney caused a partial vacuum in the basement which was replaced partly by air from the first story; this prevented some of the first-story in-

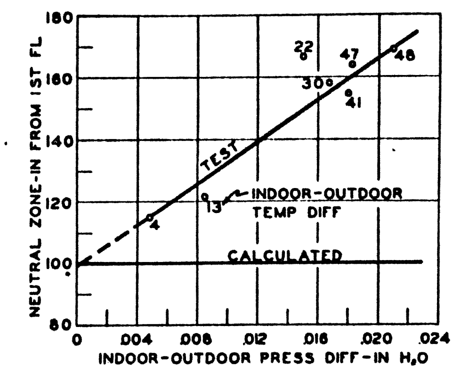

FIG. 4—EFFECT OF INDOOR-OUTDOOR PRESSURE DIFFERENCE (FIRST FLOOR LEVEL) ON LOCATION OF NEUTRAL ZONE IN I=B=R RESEARCH HOME

filtrating air from leaving the house through the second-story windows, giving an *effective* greater crack area in the second story than in the first story. The numbers by the points in Fig. 4 are the average indoor-outdoor temperature differences which give an indication of the heating plant operation. The chimney alone could cause a rise of the neutral zone above the second-story ceiling by creating a partial vacuum in the entire house.

Tests indicated air leakage from the house into the basement and into the attic. The slight attic leakage was probably around the fan-coil unit even though it was enclosed in a plastic seal. Smoke tests confirmed leakage of air through the kitchen door cracks into the basement.

Effects of indoor-outdoor temperature difference and wind velocity on indoor-outdoor static pressure difference at the first-story floor level during the heating season are shown in Figs. 5 and 6. The data have been corrected by the second approximation for 0, 35 and 70 deg F temperature differences and 0, 7.5 and 15 mph wind velocities. The curves show that a 1 deg F rise in temperature difference is equivalent to about a ¾ mph increase in wind velocity on the indoor-

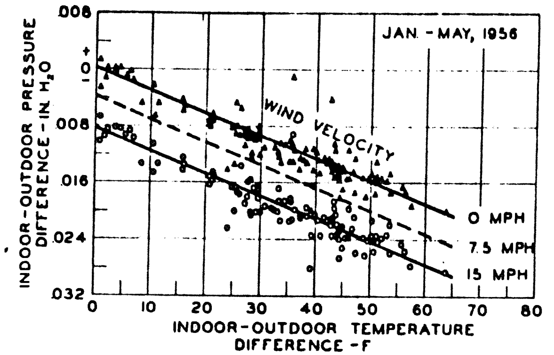

FIG. 5—EFFECT OF TEMPERATURE DIFFERENCE ON INDOOR-OUTDOOR PRESSURE DIFFERENCE IN THE I=B=R RESEARCH HOME

outdoor pressure difference. It is significant that temperature difference and wind velocity had similar effects on the pressure difference at the first-story floor level. That is, increases in temperature difference or wind velocity, caused a reduction in the indoor static pressure at the first-story floor level, making the indoor-outdoor pressure difference a larger negative amount. In buildings exposed to wind pressures, the infiltration through the windward side causes a pressure build-up inside the building which is a function of the wind velocity and the ratio of the crack areas on the windward and lee sides. Thus, it would be concluded that the wind had little direct effect on the pressures in the Research Home. However, the wind had an indirect effect on the pressures because of its effect on the air flow in the heating plant chimney. Further discussion of the chimney flow will follow later in this paper.

To determine the relationship between indoor-outdoor pressure difference and house air change rate, Fig. 7 was plotted using the static pressure difference at the first-story floor level. It can be seen that the house infiltration rate increased

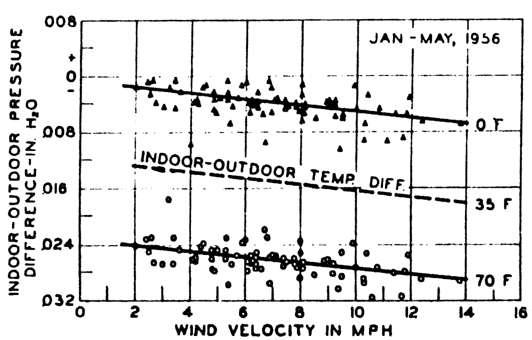

FIG. 6—EFFECT OF WIND VELOCITY ON INDOOR-OUTDOOR PRESSURE DIFFERENCE IN THE I=B=R RESEARCH HOME

rapidly for a given change in indoor-outdoor pressure difference at the first-story floor level at a small pressure difference, but slowly for a larger pressure difference. The slope of the house air change—pressure difference curve would be different if the reference pressure difference were measured at another location. If the pressure difference had been measured nearer the neutral zone, but still beneath it, the slope of the curve would have been much greater. The limiting case would occur when the pressure difference was measured at the null point—the neutral zone. For this case, the vertical axis would represent the relationship of air change and pressure difference.

The effect of the heating plant chimney on the infiltration and pressure difference has been referred to frequently. Air and combustion gases leave the Research

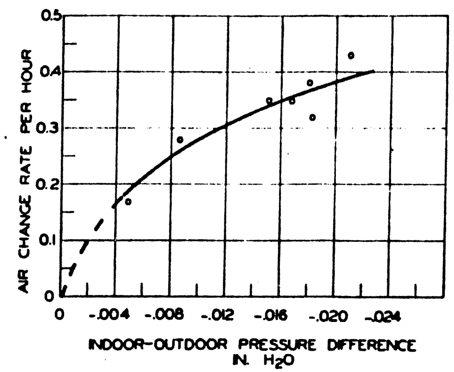

FIG. 7—EFFECT OF INDOOR-OUTDOOR PRESSURE DIFFERENCE ON FIRST AND SECOND STORY AIR CHANGE RATE IN THE I=B=R RESEARCH HOME

Home through the chimney at the rate of about 11,400 cu ft per hr[3] (0.8 air changes for the house including the basement) with an indoor-outdoor temperature difference of 35 deg F. The rate varied slightly depending upon temperature difference. It was estimated that the crackage of windows and doors in the basement and a separate flue for a gas water heater could supply about 90 to 95 percent of the air removed by the heating plant chimney. By comparing the winter and summer points on Figs. 1 and 2 it appeared that the combined effect of the chimney and bare trees increased the total infiltration by about 0.1 air changes during the winter as compared to summer conditions.

Effects of the chimney on the indoor-outdoor pressure difference at the first-story floor level are further shown by Figs. 5 and 6. It can be seen from Fig. 5 that with an increase in wind velocity there was an increase in indoor-outdoor pressure difference. This was the result of wind causing an additional air flow up the chimney, thus creating a greater suction in the basement which had a like, but lesser, effect on the first and second stories. The increase in air flow up the chimney caused by wind, in excess of that caused by temperature difference, ranged from 0 to 4000 cu ft per hr for an 8 mph wind, and from 3000 to 5000 cu ft per hr for a 15 mph wind. Thus, for a 15 mph wind the total flow in the chimney ranged from 14,000 to 16,000 cu ft per hr.

It may, therefore, be concluded that infiltration rates determined for the Research Home were slightly high due to leakage into the attic and basement, predominantly the basement. This explains the rise of the neutral zone with an increase in indoor-outdoor pressure difference, Fig. 4. The Research Home infiltration rate changed about 0.013 air changes per hr for each 4 deg F increase in indoor-outdoor temperature difference or 1 mph increase in wind velocity.

WARM AIR HEATING RESEARCH RESIDENCE NO. 2

Effect of indoor-outdoor temperature difference on infiltration rate is shown in Fig. 8. The original data have been corrected by the same method just described

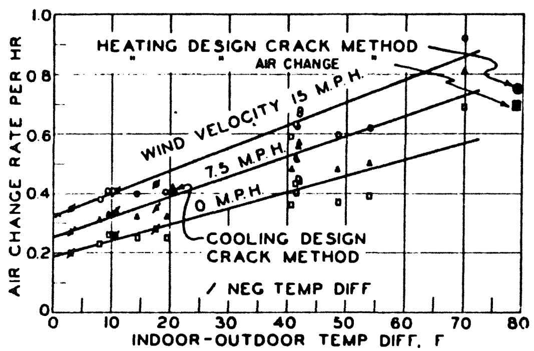

FIG. 8—EFFECT OF TEMPERATURE DIFFERENCE ON FIRST STORY AIR CHANGE RATE IN THE WARM-AIR HEATING RESEARCH RESIDENCE NO. 2

for wind velocities of 0, 7.5 and 15 mph. The data from days on which the temperature indoors was less than that outdoors have been distinguished by a slash. For each deg F change in indoor-outdoor temperature difference the infiltration rate increased approximately 0.0066 air changes or 53 cu ft per hr. The summer infiltration rates (indicated with a slash) were of the same order of magnitude as the winter rates for the same absolute value of indoor-outdoor temperature difference.

The effect of wind velocity on the infiltration rate is shown in Fig. 9 where the number of air changes is plotted as a function of wind velocity with the data corrected as before for temperature differences of 70, 35 and 0 deg. The cup-type anemometer used to obtain wind velocity during these studies was located about 23 ft above the ground level atop the weather station 40 ft north of the Residence. The recorded wind velocity may, therefore, be greater than the velocity at the level of the windows. The wind velocity at window level would be less than that measured at the anemometer and a correction for the difference would cause an increase in the slope of the air change curves. For each 1 mph increase in wind velocity the infiltration rate increased about 0.012 air changes or 97 cu ft per hr.

Part of the scatter of the points in Fig. 9 may be attributed to the effect of wind direction. Since the major part of the crack area was in the south and north walls, the highest air change rates would be anticipated when the wind was blowing from either of these directions. It was, however, impossible to draw any conclusions regarding the effect of wind direction.

The infiltration rate of the first story was estimated by the *crack* method and by the *air change* method using data given in THE GUIDE[2] 1956. In the *crack* method estimate, infiltration was assumed to occur in each room of the Residence without regard to wind direction. The length of crack used for computing the infiltration rate in each room was taken as the maximum crackage on one exposure. The total equivalent crack length used was 251 ft, or approximately 80 percent of the total equivalent crackage of the first story. The infiltration through the walls was assumed negligible. The estimated infiltration rates for design conditions during

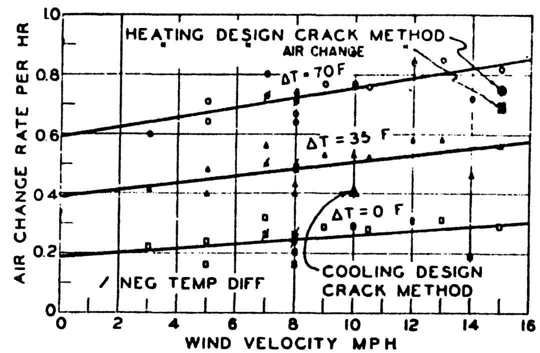

FIG. 9—EFFECT OF WIND VELOCITY ON FIRST STORY AIR CHANGE RATE IN WARM-AIR HEATING RESEARCH RESIDENCE NO. 2

heating and cooling have been plotted on Figs. 8 and 9. Design heating and cooling air change rates, which were estimated by the *crack* method and based on wind velocities of 15 and 10 mph, respectively, were 0.75 and 0.40 air changes. The design heating air change rate estimated by the air change method was 0.69 air changes. The maximum winter air change rate of 0.8, which was observed on a day when the outdoor temperature was about 0 F and the wind velocity 7 mph, was approximately 7 percent greater than that estimated by the *crack* method and 16 percent greater than that estimated by the *air change* method. The maximum measured summer air change rate of 0.36, which was observed on a day when the outdoor temperature was 95 F and the wind velocity 8 mph, was 10 percent less than the design rate. Hence, within the limits of the assumptions made in the estimate, the agreement between the design air change and that measured when design conditions were approached can be considered good. It should be noted, however, that the good agreement was obtained by over-estimating the infiltration due to wind forces and by neglecting the infiltration due to temperature difference forces. Whether similar agreement would be obtained in situations where the wind forces are predominant is problematical.

The difference between indoor and outdoor static pressure at the first-story floor level was recorded during all infiltration tests. The outdoor pressure tap was 6 ft 2 in. above the peak of the roof, and assumed to be outside the pressure region caused by the flow of air around the house. The tubing connecting the tap to the draft gage was exposed to outdoor temperature to its point of entry at the first-story floor level. Hence, the recorded pressure differentials were equivalent to the static pressure difference at the floor level. The average pressure differentials observed during each test are plotted as a function of wind velocity in Fig. 10. Since the data showed a considerable deviation from a straight-line relationship, no attempt was made to make corrections to specific conditions of wind and temperature difference. However, the available data fell on curves of temperature difference ranging from 8 to 20 F in one case and 40 to 55 F in the other. The

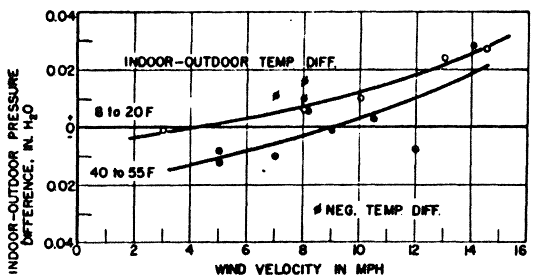

FIG. 10—EFFECT OF WIND VELOCITY ON INDOOR-OUTDOOR PRESSURE DIFFERENCE IN WARM-AIR HEATING RESEARCH RESIDENCE NO. 2

pressure build-up anticipated in structures exposed to wind forces occurred in Residence No. 2. Since the wind and temperature difference forces were acting simultaneously, one causing negative pressure differentials and the other causing positive pressure differentials, the resultant pressure difference was positive only when the effect of wind became dominant. As the temperature difference increased, the wind velocity required to cause positive pressure differentials at floor level also increased.

Results of a previous[4] investigation showed that wind direction had an appreciable effect on the pressure differentials at floor level because of different crackages in the exposures of the house. In earlier studies, the effects of temperature difference were not considered, but the trends established for each exposure were similar to those of Fig. 10. With the wind blowing from some directions, namely the east, the pressure differences were always negative during the winter because of the small amount of crackage in the east exposure.

As mentioned previously, the choice of the location of the reference pressure influences the slope of the curves of house air change as a function of pressure difference. When both wind and temperature difference forces influence the reference pressure, as was the case in Research Residence No. 2, a family of curves would be required to show the relationship of total infiltration and pressure difference at the floor level. At zero pressure difference, the slopes of the curves would change from negative to positive when moving in a positive direction along the pressure

difference axis. Since the data were limited, it was impossible to determine the relationship of infiltration and static pressure difference at the first-story floor level. Using the crack data for the first story and basement, calculation shows that the neutral zone is located approximately 30 in. above the first-story floor. For this estimation it was assumed that no air was passing through the walls or the first-story ceiling, that the resistance to air flow from the basement to the first story was negligible and that no air was leaving through the chimney.

With the crack areas around doors and windows known and the neutral zone located, it was possible to compute the relationship between indoor-outdoor temperature difference and wind velocity giving the same amount of infiltration in the

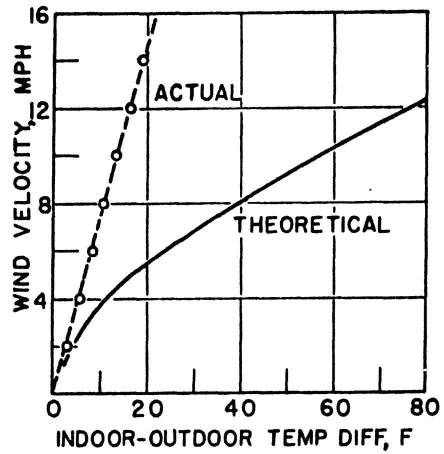

FIG. 11—THEORETICAL AND ACTUAL RELATION BETWEEN INDOOR-OUTDOOR TEMPERATURE DIFFERENCE AND WIND VELOCITY GIVING THE SAME INFILTRATION RATE

first story. In this estimate it was assumed that infiltration due to wind forces would occur through one-fourth of the total crack of the first story and that due to temperature forces would occur through the total crack of the residence located below the estimated neutral zone. The flow through the cracks was assumed to vary with the square root of the pressure difference. This relationship is shown in Fig. 11 together with the actual relationship determined from the zero wind velocity and zero temperature difference curves of Figs. 8 and 9, respectively. Whereas the theoretical relationship indicates that the wind is the dominant effect, the results of the studies indicate clearly that the effect of temperature difference was more pronounced.

This difference can be explained if it is assumed that the flow resistance of the first-story ceiling is comparatively low. A low resistance in the ceiling would raise the neutral zone, and thus increase the amount of infiltration caused by temperature difference. It would, however, have very little influence when the wind is the only active force. It should be noted that the ceiling of Research Residence No. 2 is constructed of pressed cement-asbestos boards with taped joints. Even though no cracks were apparent, it was not possible to inspect the tightness of all joints. Recorded wind velocity and indoor-outdoor pressure difference data show that with zero wind there was as much suction at the floor level of the first story as theoretical calculations show when the neutral zone is assumed to be just at the ceiling level.

Further explanation of the difference is found in the effect of the flow of gases in the chimneys. A considerable amount of air was leaving the basement through the chimneys during winter, both combustion air for the furnace and the water heater and air entering the smoke pipes through the draft diverters. The volume varied somewhat with outdoor temperature, but was an average of 4500 cu ft per hr, or approximately half an air change for the basement. Since this air was taken directly from the basement, it would seem reasonable that it would be replaced with outdoor air leaking in around the basement windows and air leaking down from the first story. Smoke tests showed, however, that during the heating season, air was always streaming from the basement into the first-story rooms. The magnitude of this air flow could not be determined.

As the amount of air leaving through the chimney increases, the suction in the basement increases, causing a decrease in the amount of basement air entering the first story. Consequently, the chimney causes the neutral zone to shift upward in the same manner as a low flow resistance in the first-story ceiling. It is likely that both factors contributed to the difference of the theoretical and actual relationships between wind velocity and temperature difference. The extent to which each factor affected the difference could not be ascertained from available data.

Although no helium was released into the basement during the studies, within a short period of time there was a considerable amount of helium in the basement air. During the winter studies, the basement helium concentration was attributed solely to leaks in the ductwork and furnace casing since, as was mentioned before, smoke tests showed that air was always streaming from the basement to the first story. During the summer studies, a portion of the helium in the basement air could be attributed to leaks in the ductwork; however, since the concentration of helium increased to a much higher level than had been noticed during the winter studies another source of helium was suggested. Since the theoretical location of the neutral zone was estimated 30 in. above the first-story floor, it was assumed that the air would flow from the first story to the basement. Smoke tests confirmed this assumption. This mixing of basement air and first-story air by leakage from the air distribution system and by gravitational effects had some influence upon the rate of decay of helium concentration in the first-story rooms. Consequently, there may be minor errors in the air change rates calculated from the observations.

Comparison of Results for the Two Residences

When comparing the results from the 2 houses it should be noted that the houses are similar in size and have almost equal crackages. The volumes of the 2 houses, excluding the basements, differ by only 1309 cu ft, the Research Home having the greater volume. The distribution of the cracks on the 4 exposures is almost the same in the 2 houses.

Although the houses are similar, their infiltration rates differ considerably, especially at high wind velocities and high temperature differences. With a 15 mph wind and a 70 deg F temperature difference, the infiltration rate of Research Residence No. 2 is about 50 percent higher that that for the Research Home. This difference can be explained by considering several factors. The Research Home is well protected from wind; this decreases the wind effects on infiltration. Wall and ceiling construction of the Research Home (plaster) is tighter than that of Residence No. 2 (plywood and pressed cement-asbestos board panels fastened with screws); this decreases the effects of both wind and temperature difference.

The tight construction of the Research Home and the protection from wind is partially offset by the stack effect of the house. Since the Research Home is 2 stories high and Residence No. 2 is one story, there is a greater potential for air flow into and out of the Research Home than in Residence No. 2.

Difference in exposure to wind was shown by the measured indoor-outdoor pressure difference for the 2 houses. In the Research Home the wind increased the vacuum at the first-story floor level through its effect on the chimney draft. In Research Residence No. 2 a pressure build-up occurred at floor level when the effect of wind was greater than that of temperature difference. The effect observed in Residence No. 2 would be anticipated for a structure exposed to wind forces.

The heating plant chimney had a much greater effect on the infiltration in the I=B=R Research Home. The flow of gases in the chimney was on the average equal to 0.8 to 1.0 air changes for the entire house including the basement. Most of the air flow in the chimney infiltrated through cracks around the basement windows and the vent on a gas-fired hot water heater. However, the chimney caused the pressure difference at the first-story floor level to be greater than predicted through its effect on the location of the neutral zone. In Residence No. 2 the flow of chimney gases was equivalent to 0.27 air changes for the first story and basement, and the chimney apparently had a small effect on the infiltration. The influence of the chimney caused air to stream from the first story to the basement in the Research Home, but in Residence No. 2 the effect of the chimney was so small that the natural flow from the basement to the first floor was not interrupted.

As was mentioned previously, the validity of the tracer gas technique for measuring infiltration was questionable because of the extremely high diffusion rate of helium. It is conceivable that helium diffuses through the walls, ceilings and floors, thus indicating a higher than actual infiltration rate. The bottom curves of Figs. 1, 2, 8 and 9 suggest this fact since the curves do not pass through the origin, but intersect the air change axis, and indicate infiltration when there is no driving force (zero wind velocity and zero temperature difference). Furthermore, at zero wind velocity and zero temperature difference, the air change rate for the Research Home is about 0.12 and that for Residence No. 2 is about 0.19; this denotes that there would be more diffusion through the walls of Residence No. 2 than through the walls of the Research Home. It is apparent that helium would diffuse more readily through the walls of Residence No. 2 than through the walls of the Research Home if it is assumed that the wall construction resistance to water vapor diffusion is an index of its resistance to helium diffusion.

Conclusions

1. Good agreement between measured and calculated air change rates was obtained. The good agreement was a result of over-estimating the effect of wind forces and neglecting the effect of temperature difference forces. In the *crack* method the maximum in-

filtration in each room is used to obtain the total infiltration for a structure. Since the wind can act on only one or two exposures, the design precedure leads to an over-estimate of the total infiltration caused by wind. If the 2 houses studied had been located in other climates, the agreement between measured and calculated infiltration rates would not have been as good because the temperature difference was an important factor in both houses.

2. The Research Home, which is located on a typical city site surrounded by large trees and houses, has a considerably smaller infiltration rate at a given wind velocity measured above tree top level than that of Research Residence No. 2, which is located on a relatively open site, free of trees, and typical of new housing developments.

3. The flow of flue gases in the chimneys of the 2 houses during the winter had an appreciable effect on their infiltration rates. The effect was more pronounced in the Research Home, which is a 2-story structure.

4. Loss of helium by diffusion through walls and ceiling may have caused the *apparent* air change rates to be greater than the actual rates.

ACKNOWLEDGMENTS

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REFERENCES

1. ASHAE RESEARCH REPORT No. 1614—Measurement of Infiltration in Two Residences, Part I—Technique and Measured Infiltration, by D. R. Bahnfleth, T. D. Moseley and W. S. Harris (ASHAE TRANSACTIONS, Vol. 63, 1957, p. 439).

2. HEATING VENTILATING AIR CONDITIONING GUIDE 1956, Chapter 11, Infiltration and Ventilation, Table 2, p. 230 (published by the AMERICAN SOCIETY OF HEATING AND AIR CONDITIONING ENGINEERS, New York).

3. Heat Supplied to I=B=R Research Home from the Inside Chimney, by W. S. Harris and R. J. Martin (Engineering Experiment Station *Bulletin No. 407*, University of Illinois, Urbana).

4. Outdoor Air Supply and Ventilation of Furnace Closet Used with a Warm-Air Heating System, by R. W. Roose, N. A. Buckley and S. Konzo (Engineering Experiment Station *Bulletin No. 427*, University of Illinois, Urbana).

DISCUSSION

T. C. MIN, Cleveland, Ohio (WRITTEN): The authors are to be commended upon this contribution to the information on infiltration in residences. During the past year, research on entrance infiltration in multi-story buildings was undertaken at the ASHAE Research Laboratory. The results of the project are now being prepared into a report. It will be of interest to the members of the ASHAE to know that some of the findings, as pointed out by the authors, are very similar to those conducted at the Laboratory.

In Fig. 5, Part II, of the paper, at a wind velocity of 15 mph and zero indoor-outdoor temperature difference, the outdoor-indoor pressure differential is 0.008 inch of water which corresponds only to a wind velocity of less than 4 mph. Also in Fig. 6, Part II, at the zero indoor-outdoor temperature curve, the outdoor-indoor pressure differentials vary approximately only 0.004 in. of water for wind velocities from 2 to 14 mph.

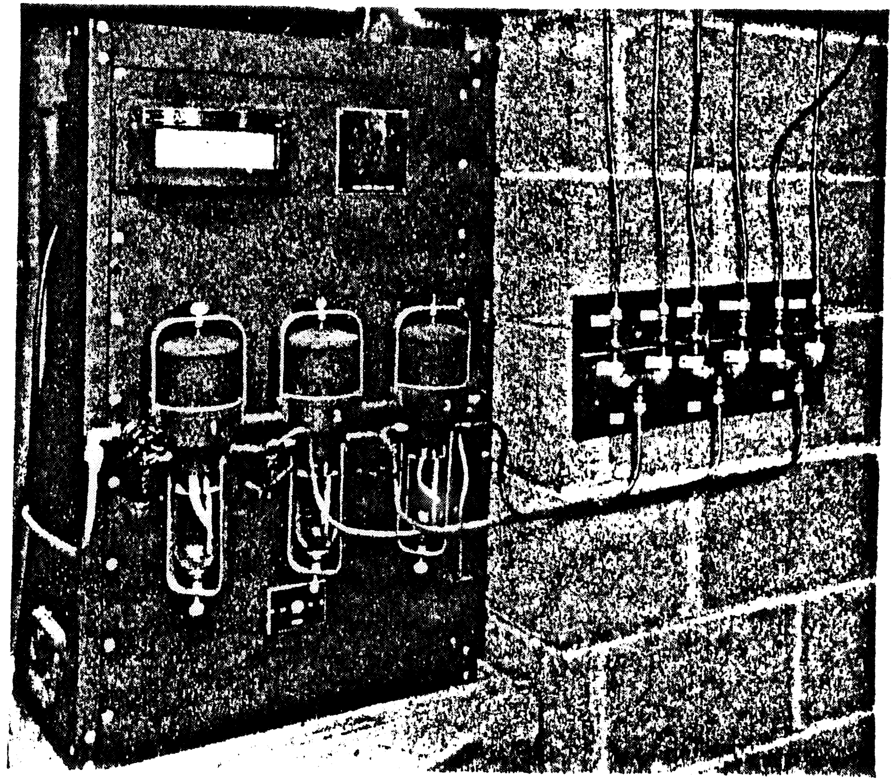


FIG. A—VIEW OF THE KATHAROMETER INSTALLED

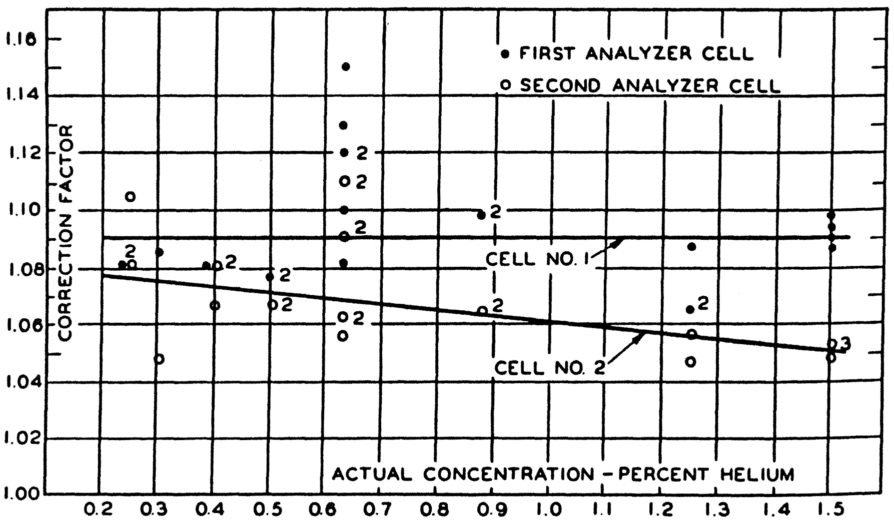
In the field tests of the ASHAE entrance infiltration study, it was found on some very windy days with wind velocities of more than 20 mph, according to the local weather station's report, that the wind velocities measured windwardly at the curb of the street near the building entrance were not more than 6 mph. The wind in the direction perpendicular to the entrance was not more than 2 mph, which is equivalent to a pressure differential of less than 0.002 inch of water. The difference in wind velocities between the weather station's reading and the test value is obvious since the former observed the wind at the top of the building in an open space such as an airport, while the latter determined the velocity under conditions with obstructions, especially in the congested downtown area.

There are also 2 minor points which the writer would like to check with the authors:

1. When the outdoor-indoor pressure differential is zero, is it true that the neutral zone could be any place instead of only one place, 100 in. above the floor as indicated in Fig. 4, Part II?

2. Is it correct that when the time increases, the concentration of helium decreases? In other words, is it in order that a negative sign may be placed in the equation $Vdc = nVc\,dt$ in Part I?

C. W. COBLENTZ,†† Washington, D. C. (WRITTEN): A commercial helium katharometer purchased by the American Society of Heating and Air-Conditioning Engineers



Numerals next to points indicate number of observations
Correction factor equals Actual Concentration/Instrument Reading

FIG. B—CALIBRATION OF THE ASHAE KATHAROMETER

was loaned to the National Bureau of Standards for an evaluation of its performance and for studies of air infiltration in the Test Bungalow at the Bureau. The instrument is a thermal conductivity meter designed to indicate concentrations of helium in air in the range of zero to 1.6 percent. Since the thermal conductivity of helium is approximately 6 times that of air, mixtures of helium and air, even in low concentrations of helium, have a measurably greater thermal conductivity than pure air. Thus by using helium as a tracer gas a katharometer of this type can be used to measure air leakage into buildings or other closed spaces. A photograph of the instrument is shown in Fig. A.

†† It is to be noted that the discussion presented here by Mr. Coblentz is a paper entitled *Performance Characteristics of the ASHAE Katharometer*, by C. W. Coblentz, P. R. Achenbach, and E. M. Tierney, all of the staff of the National Bureau of Standards.

Description of the Instrument: This instrument is equipped with 3 separate thermal conductivity cells so that 3 samples of helium-air mixture can be drawn simultaneously for concentration determinations. These samples are drawn through the apparatus by a motor-driven vacuum pump and the source of each sample was determined by an arrangement of tubes and stopcocks shown at the right in Fig. A.

Because the thermal conductivity of air, or of an air-helium mixture is affected by its moisture content, the samples were bubbled through water and were practically saturated when reaching the analyzer. The gas bubblers can be recognized under each of the cells on the photograph, which also shows the helium indicator at the upper left of the instrument.

Each of the thermal conductivity cells contains 2 platinum resistance elements which were heated with a constant electric current and which form 2 legs of a Wheatstone bridge circuit. The resistance elements of each cell were installed in separate cavities drilled in a brass block so the wall temperatures of the 2 cavities would be equal. One

TABLE A—NUMBER OF MEASUREMENTS AND MAXIMUM, MINIMUM, AND MEAN VALUES OF CORRECTION FACTORS

Actual Concentration	No. of Observations Made		Correction Factors Determined					
			Maximum		Minimum		Mean	
	Cell #1	Cell #2	Cell #1	Cell #2	Cell #1	Cell #2	Cell #1	Cell #2
0.633	6	7	1.149	1.100	1.083	1.056	1.117	1.081
1.504	4	4	1.098	1.052	1.086	1.048	1.092	1.051

cavity was hermetically sealed; the other cavity had openings at each end to permit the passage of the gas sample. Thus, when a sample containing helium was drawn through one cavity, the resistance element in that cavity was cooled below the temperature of the other in the sealed reference cavity. This cooling effect lowered the resistance of the wire causing an imbalance of the Wheatstone bridge circuit which was measured by a galvanometer. Since the cooling effect is directly related to the percentage of helium present in the sample, the galvanometer can be calibrated in percentage of helium.

The selector switch, shown in the upper right of Fig. A, permitted rapid observation of the helium concentration in any of the 3 samples passing through the katharometer, after initially flushing out the sampling lines.

The rate of flow through the 3 cells can be regulated individually by the needle-valve controls shown in the photograph at the left of each bubbling chamber. The cells were equipped with water jackets to prevent over-heating of the cells and to maintain a steady temperature of the cells. These water jackets are shown connected in series in the photograph. Water flow through the jackets can be controlled by the valve at the left of the photograph. Water was not passed through the jackets during the tests of the instrument since the room air temperature was controlled by a thermostat.

Accuracy of Helium Concentration Indications: Tests were made to determine the accuracy of the instrument in indicating the absolute concentrations of helium in air. Pure helium was taken from a high-pressure storage cylinder and transferred into water-sealed flasks where it was held at atmospheric pressure. The displacement method was used to transfer the helium from these flasks to water-sealed sampling flasks and helium-air mixtures were prepared in concentrations ranging from 0.3 percent to 1.6 percent helium. Several samples of each concentration were passed through the katharometer and the correction factor for each measurement was determined as the ratio of the known helium concentration to the indicator reading. Fig. B shows the correction factors plotted against the known concentrations. Fig. B shows considerable scattering of the individual observations for a given helium concentration. A correction factor curve has been drawn for each of the 2 cells used although it is recognized that the plotted observations do not define any precise line.

The effect of scattering on the correction factors determined for actual concentrations of 1.504 percent and 0.633 percent is shown in Table A which gives the number of measurements made with 2 cells of the apparatus and the maximum, minimum, and mean values for the correction factors.

TABLE B—EFFECT OF CORRECTION FACTOR OF CELL #2

HELIUM CONCENTRATION		CORRECTION FACTOR		AIRCHANGE		ERROR, %
INITIAL	FINAL	INITIAL	FINAL	APPARENT	ACTUAL	
1.5	0.522	1.050	1.071	1	0.981	1.9
1.2	0.442	1.057	1.073	1	0.985	1.5
0.9	0.331	1.063	1.076	1	0.988	1.2
0.6	0.221	1.070	1.078	1	0.991	0.9

It will be noted in Table A that the maximum deviation of the values determined for the correction factor at an actual concentration of 0.633 percent was 0.066 for the first cell and 0.044 for the second cell, whereas for an actual concentration of 1.504 percent the corresponding deviations were only 0.012 and 0.004. The deviations in indicated helium concentration for a given actual concentration are believed to be caused in part by variations in the heat transfer from the resistance elements to the brass blocks as discussed in the following section.

A constant correction factor would not cause an error in an infiltration rate determination. Thus, if the horizontal line shown for cell No. 1 in Fig. B were considered to be the true average performance of that cell, no error in infiltration determinations would result from the fact that the indicated value was 9 percent below the actual concentration. A correction factor curve of the slope shown for cell No. 2 in Fig. B would cause errors as shown in Table B for one complete airchange in a space.

Drift of Zero Adjustment and Parallax: The position of the hand on the helium indicator fluctuated around the zero point as much as 1½ scale divisions, corresponding to 0.03 percent helium, during a period of 7 hours when a flow of pure air was initiated through the cells. The drift of the indicator appeared to depend in part on whether or not a steady state of heat flow existed between the platinum resistance elements in the cells and the enclosing brass block. When air flow was initiated through the cells after having the heating elements energized without gas flow overnight, the zero position of the indicator hand changed about one scale division for each cell during the first hour of operation. During the next 6 hours the indicator position on cell No. 2 changed an additional half scale division in the same direction whereas that for cell No. 1 changed a half scale division in the opposite direction. One and a half scale divisions corresponds to an error of 2 percent in the absolute value at 1.5 percent meter reading, 5 percent at 0.6 percent meter reading, and 15 percent at 0.2 percent meter reading.

Errors in reading the curved indicator scale caused by parallax are considered to be of the order of one-fourth scale division, or 0.005 percent helium. Thus, parallax

could cause a 2½ percent error in the reading for a concentration of 0.2 percent helium.

Uniformity of Response of Three Cells: In order to determine whether or not the 3 cells were identical in their response, samples of a helium-air mixture were drawn continuously from the same station in the Test Bungalow for a period of about 110 minutes and passed through all 3 cells of the instrument while the helium concentration decreased from an initial value of about 1 percent to a final value of about 0.2 percent. Because the Test Bungalow is completely enclosed in an insulated enclosure, equal temperatures could be maintained inside and outside the building. Also, the air conditioning blowers in the space surrounding the building produced a constant air velocity outside the house.

TABLE C—UNIFORMITY OF RESPONSE OF THREE CELLS TO IDENTICAL AIR-HELIUM MIXTURES

	CELL #1	CELL #2	CELL #3
First period (0 to 72 min)			
Initial Concentration, %	0.998	0.965	0.885
Final Concentration, %	0.500	0.492	0.449
Airchange Rate	0.576	0.560	0.563
Ratio of Airchange Rate, %, to that of Cell 2	102.4	100.0	100.3
Second period (80 to 110 min)			
Initial Concentration, %	0.370	0.384	0.343
Final Concentration, %	0.182	0.194	0.171
Airchange Rate	1.416	1.364	1.380
Ratio of Airchange Rate, %, to that of Cell 2	103.8	100.0	101.3

Therefore, the infiltration rate of the building could be maintained steady over an extended period of time. Inside and outside temperatures and the air movement in the enclosure were not changed during the entire test. In order to obtain an accelerated infiltration rate for a portion of the test, the exhaust fan in the attic of the Bungalow was operated during the last 30 minutes of the test.

Fig. C shows the observed helium concentrations plotted against time on semi-logarithmic paper and the best-fitting straight line drawn for each cell. After tracer-gas measurements had been taken at 5 minute intervals for a period of 70 minutes, the attic fan was turned on. The resulting change of the infiltration rate is indicated by the change in slope of the 3 nearly parallel lines. Some of the individual concentration values deviate from the straight line which is the criterion for a constant infiltration rate. Although there is a maximum difference of 14 percent in the helium concentration indication among the different cells, the difference between the computed infiltration rates was much smaller, as shown in table C.

Table C shows the initial and final concentrations given by the lines fitted to the data for each cell and for the 2 parts of the test. The airchanges which occurred during these periods were calculated as the natural logarithms of the ratios of the helium concentrations at the beginning and at the end of the period. The airchange rate during the first 72 minutes of the test computed from Cell No. 3 was 0.3 percent higher than for Cell No. 2, and the airchange rate computed from Cell No. 1 was 2.4 percent higher than for Cell No. 2. For the second period of the test the corresponding differences were 1.3 and 3.8 percent, respectively. The best-fitting lines shown in Fig. C for Cells 2 and 3 are nearly parallel thus indicating that the infiltration rate computed from these 2 cells would be nearly the same.

Effect of Gas Pressure at the Cell: The instrument was found to be practically insensitive to atmospheric pressure fluctuations or pressure differences that may arise from long sampling lines. A test showed that a change in pressure at the inlet of the instrument from 36 in. of water positive pressure to 36 in. of water vacuum increased the indicator reading by only 0.02 percent of helium at the middle of the scale.

Effect of Sampling Flow Rate: A test was made to determine the effect of the gas-flow rate through the bubblers on the indicator reading. For this purpose an orifice flow meter was installed in the sampling line and the helium-air mixtures were drawn from water-sealed flasks containing 0.45 and 0.65 percent of helium in air, respectively. The results of this test are plotted in Fig. D, which shows the correction factor for air flow rates from 40 to 378 cubic centimeters per minute.

Fig. D shows an increasing correction factor for gas flow rates in the range from 40 to 250 cc per min and a decreasing correction factor for flow rates above 250 cc per min.

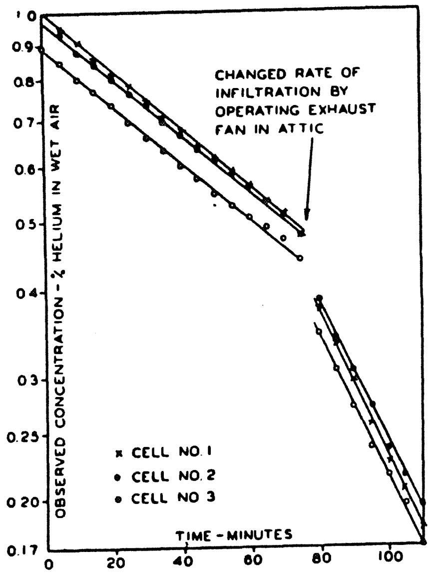


Fig. C—Response of Three Cells under Identical Conditions

A correction factor of unity was observed for a flow rate of about 125 cc per min. There was some scattering of the observed values, but the relation between correction factor and flow rate was similar for the 2 levels of helium concentration used. The curve fitted to the plotted values shows only one percent change in correction factor in the range of flow rates from 175 to 350 cc per min.

Effect of Length of Sampling Line: The time lag of the katharometer was determined by alternately introducing a helium-air mixture, from a 6-gallon water-sealed can, and pure air from the room into 2 of the test cells and averaging the readings during 5 such cycles. The results of these tests with samples drawn through 3 ft of ¼-in. copper tubing are shown in Fig. E. Fig. F shows the result of a similar test using 30 ft of ¼-inch tubing. It will be noted that near balance was reached after 3.5 minutes with the 3 ft sampling line, whereas with a 30 ft line the indicator required about 5 minutes to arrive at near balance. Thus, the time constants were about 55 seconds and 2 minutes for the 3-foot and 30-foot sampling lines, respectively.

Conclusions: The characteristics of the specimen katharometer described indicate that the following practices should be followed during use to minimize errors in infiltration measurements.

(1) Air should be drawn through the cells for at least an hour before any measurements are taken.

(2) Helium concentrations in the range from 0.4 to 1.4 percent should preferably be used to reduce the importance of the error caused by drift and parallax.

(3) The rate of gas flow through the bubblers should preferably be kept constant, although variation in the range from 200 to 350 cc per min was shown to cause an error of one percent or less.

(4) The shortest possible sampling lines should be used and appropriate consideration given to the lag of the instrument at the beginning of a test.

(5) Numerous readings of concentration should be taken during any test to average out the errors caused by drift and parallax.

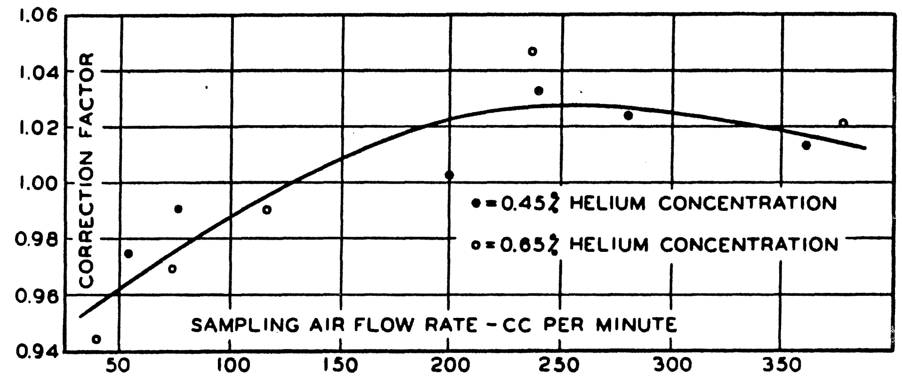


Fig. D—Effect of Sampling Air Flow Rates

(6) The use of a decay range in the lower third of the indicator scale would result in lower errors from the slope of a correction factor curve such as shown for Cell No. 2. However, this advantage would probably be more than offset by the greater error resulting from drift in the lower third of the scale.

Observing the precautions summarized will minimize the errors in results caused by drift of the indicator needle, parallax, and variability of gas flow. This study of the characteristics of the ASHAE katharometer indicates that it is a satisfactory instrument for infiltration measurements.

R. A. Parsons, Lansing, Mich., (Written): These two papers provide interesting information on a subject that needs clarifying. More good work of this type should be encouraged. My comments are presented for the purpose of obtaining more effective use of the data.

Conclusion 4 of Part II regarding loss of helium by diffusion through walls was not considered in comparing measured and estimated air change rates. Furthermore, the first sentence of Conclusion No. 1 of Part II, regarding good agreement between measured and estimated air change rates, is questionable when the data is examined carefully, and when adjusted for the 0.19 changes per hour due to diffusion as in the accompanying Table D for Warm Air Heating Research Residence No. 2.

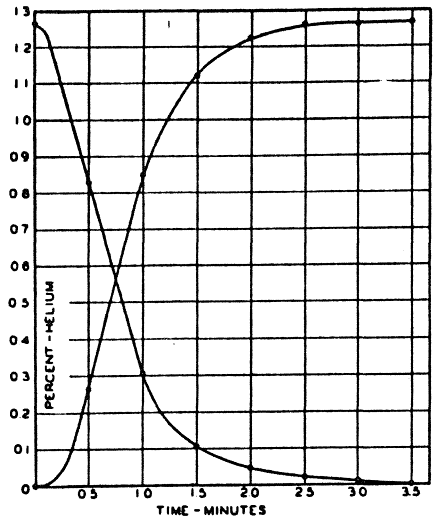


FIG. E—LAG OF KATHAROMETER RESPONSE WITH 3 FT TUBING

The poor agreement between measured and estimated air change rates both at design and average conditions indicates the following conclusions.

1. The statement on page 244 of THE GUIDE 1957 that is very widely used because of its simplicity should be reworded as follows: *An allowance of one-third air change per*

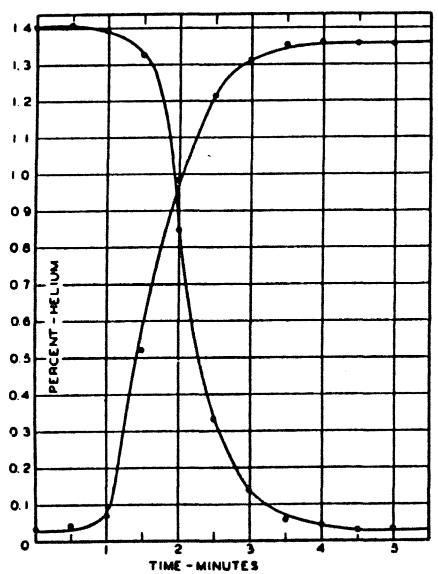


FIG. F—LAG OF KATHAROMETER RESPONSE WITH 30 FT TUBING

hour for all sources of air leakage for the entire volume may be considered average for a well constructed residence at average conditions of wind and temperature difference.

2. All values in Table 4, page 245 of THE GUIDE 1957 should be revised considerably, including the footnote. The title of Table 4 should be reworded as follows: *Air Changes Taking Place Under Design Conditions in Typical Residences, Exclusive of Air Provided for Ventilation.*

3. More measurements of infiltration rate should be made at both design and average conditions of wind and temperature difference.

TABLE D—DESIGN AND AVERAGE RATES OF INFILTRATION FROM THE GUIDE AND FROM THE AUTHORS' PAPERS

ITEM No.	BASIS OF INFORMATION	DESIGN RATE OF INFILTRATION, AIR CHANGES PER HOUR	AVERAGE RATE OF INFILTRATION, AIR CHANGES PER HOUR
1	1956 Guide, p. 232 1957 Guide, p. 244	Not specified (Obviously more than 1.0)	1.0 (wind velocity and climate not specified)
2	1956 Guide, p. 233 1957 Guide, p. 245	Not specified (Obviously more than 0.69)	0.69 (Text of Part II)
3	1956 Guide, p. 230* 1957 Guide, p. 242	0.75 (at 15 mph)	0.12 (at 5 mph)
4	1956 Guide, p. 230 1957 Guide, p. 242	—	0.40 (at 10 mph)
5	Text of Part II	0.69 (based on Item 2 above)	—
6	Table 6 of Part I	0.61 (at 7 mph, test #5 70 deg. temp. diff.)	—
7	Table 6 of Part I	0.38 (at 14 mph, test #6 54 deg. temp. diff.)	—
8	Table 6 of Part I	—	0.36 (at 10 mph, test #2)
9	Table 6 of Part I	—	0.33 (at 5 mph, test #3)
10	Table 6 of Part I	—	0.22 (at 5 mph, test 12)

* Double-hung wood sash windows, weatherstripped.

4. All measurements should be adjusted for loss of helium by diffusion through walls and ceiling so they can be compared readily with other information.

AUTHORS' CLOSURE (Mr. Harris): Mr. Min's comments relative to the observed wind velocity in proximity to a building as compared to that reported for the area by the weather bureau are interesting. A number of years ago glass surface temperatures were measured on several windows in the Research Home during winter weather. These observations also indicated that the actual wind velocity at the wall of the building seldom exceeded 2 to 5 mph even when weather bureau observations indicated much higher wind movements. On the other hand, it is quite probable that wind effects would be more pronounced for houses in more exposed locations than that of the Research Home.

In answer to Mr. Min's first question, the abscissa of Fig. 4 is indoor-outdoor static pressure difference measured at the first-story floor level. Thus, it would seem that at an indoor-outdoor pressure difference of 0.000 in. of water the neutral plane should be at 0 in. above the floor of the first story. Fig. 5 shows that an indoor-outdoor pressure difference of 0.000 in. of water represents a day having a low indoor-outdoor temperature difference and low wind velocity. Therefore, it would be expected that the pressure difference between different elevations in the house would be zero also, and the neutral plane could be assumed at any level.

Mr. Min is correct that there should be a minus sign in the equation $Vdc = nV\,dt$. While the minus sign was omitted in this equation, it apparently was considered in the solution of the equation.

Mr. Parsons expresses the opinion that the infiltration rates shown in Table 4, page 245 of the ASHAE GUIDE should be reduced. The authors feel that results obtained in only 2 houses are not sufficient to warrant changes in the material now published in THE GUIDE. They do agree that additional tests of this type are desirable and should be encouraged.