VENTILATION RESEARCH IN OCCUPIED HOUSES*

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Summary.

The paper describes the extension of experimental studies of natural ventilation o the processes in occupied houses. The results are given of measurements of the ir-change rates and the consequent rates of heat loss in occupied and unoccupied ouses on two sites, one exposed and the other sheltered. Subsidiary observations of he wind pressures on the houses and of the window-opening habit of the occupants re discussed. These are used in conjunction with the results of a regional survey f the temperatures maintained and the window-opening habits in local authority houses, to extend the application of the results to other housing. It is estimated that the average rate of heat loss by ventilation from occupied houses will range from 6 to 8 therms per week, depending on the exposure of the site and on the air flow induced by the heating system: these values correspond to air-change rates between 2 and 3 per hour.

1. INTRODUCTION.

RESEARCH on ventilation at the Building Research Station has in recent years been concerned mainly with the natural ventilation of houses. In particular, research has been undertaken on two groups of experimental houses where heating trials were in progress, and in these the adequacy of the ventilation systems and the rates of heat loss by ventilation have been studied. The results of measurements made in twenty unoccupied houses at Abbots Langley have already been reported,[1] and these were followed by measurements of the air-change rates in the rooms of eight occupied houses at Bucknalls. Both sets of measurements showed the rates of air change in the rooms to be adequate: consequently, later studies in the occupied houses were directed on the rates of air change of the houses and the rates of heat loss due to ventilation. The measuring technique was adapted for this purpose and a comprehensive series of measurements was made on both sites during the winters of 1948–49 and 1949–50; the results obtained are presented in this paper.

The results of such studies, if they are to be extended to other dwellings, must be viewed within the framework of the physical processes involved. The relevant factors have been discussed in detail in an earlier paper,[2] but a brief summary is given below as a background to the development of the experimental work.

2. NATURAL VENTILATION.

The rate of air flow into and out of a house depends on the magnitude of the aeromotive forces and the resistances presented to these forces. The aeromotive forces may be caused either by wind or by a difference in the density of the air inside and outside the house. The wind pressure will depend on the interrelation between the speed and direction of the wind and the exposure of the house; the difference in air density, which is produced by temperature differences, may be due either to a heated flue or to the air inside the rooms being heated above the temperature of the air outside—in the latter case the aeromotive force is known as stack pressure. The openings through which air may be driven by these forces are air bricks, ventilators, flues, open windows, internal and external doors, or if these be shut, the gaps between such units and their frames. The pattern of air flow will depend both on the forces and the openings. In general terms, when the motive force is wind pressure, air will enter the house through openings in the windward wall and leave through openings in leeward walls and through flues or ventilation ducts to the roof; when the motive force is caused by a heated flue, the flow will be along the path of least resistance from openings in any wall to the flue and thus to outside; when stack pressure is the motivating force, air will enter through inlets at low level and leave through outlets at high level. Thus for each force there is an associated pattern of air flow, and the rate of air flow will be approximately proportional to the square root of the pressure and to the effective area of the openings related to this pressure.

If H is the pressure, a the effective area of the openings and R the air-change rate of the house, then

$$R \propto aH^{\frac{1}{2}}.$$

If v is the wind speed, and $\triangle T$ the difference between the temperatures of the air inside and outside the house, then H will be proportional to v^2 or to $\triangle T$. If a_1 and a_2 are the effective areas of the openings associated with these pressures, then

$$R \propto a_1 v \text{ (for wind pressure)},$$
$$\text{and } R \propto a_2 \triangle T^{\frac{1}{2}} \text{ (for stack pressure)}.$$

For a heated flue, the rate of air flow may be taken as constant, so that in this case the rate of air change is given by

$$R = A \text{ (where } A \text{ is a constant)}.$$

3. OUTLINE OF EXPERIMENTAL WORK.

Since one of the important motive forces causing air change is wind pressure, it was desirable to express the wind pressure across the two sites in terms of wind speed and direction. The pressure measurements around the houses at Abbots Langley have already been reported[1]; a similar set of measurements was carried out at Bucknalls Close, so that a quantitative comparison of the exposure of the two sites could be made.

The methods used to measure the air-change rate of a house and the consequent rate of heat loss have already been described.[3] To obtain a representative sample of results, the rates were measured throughout the heating season at random times during the day and night. At Bucknalls the houses varied in the degree of thermal insulation of the shell, but since the heating appliance and ventilating systems were alike, measurements were taken at random in the houses. At Abbots Langley the heating systems varied from house to house, but so far as the differences affected ventilation, could be grouped into three main categories according to the magnitude of the air flow induced by heated flues; on this site, therefore, an equal number of measurements was taken from each category. In all, over 200 measurements were taken of ventilation rates of houses, involving approximately 2,000 measurements of the rate at whic

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the tracer gas decayed in the individual rooms. At the time of each measurement, the wind speed and its direction, the inside and outside temperatures and the positions of the openable windows were recorded.

The only other factor which is not normally recorded in connection with the heating trials, but which influences the heat lost from a house, is the window-opening habit. Daily observations of the number and position of the open windows and their degree of opening on both sites were taken at random times between 09.00 and 18.00 hours from October to April. At Bucknalls this was supplemented by reports from the tenants of the windows they kept open at night. It was found that on the average these reports corresponded with the observations by day except that the windows downstairs were kept closed at night. In the absence of such information from Abbots Langley, it was assumed that the average habit at night would conform to this fairly typical tenant behaviour. The areas of the openable sections were similar on both sites, being about 250 sq. in. for a top-hung vent-light and 1,000 sq. in. for a side-hung casement.

For convenience the results from the two sites are presented separately below in Sections 4 and 5. It will be seen that the development of the analysis has been along similar lines in the two cases, viz. the measured air-change rates have been related to the acting aeromotive forces and to the window-opening habit of the tenants. A better understanding of the processes is obtained from a comparison of the two sets of results, and to enable this to be done the results are summarised in the table in Section 6; this table is also used for later discussion of the extension of the results to other housing.

4. RESULTS OBTAINED ON EXPOSED SITE (ABBOTS LANGLEY).

4.1 Introduction.

The houses on this site have been described previously.[1] The ventilation measurements were made unobtrusively and remotely, so that there was little interference with the normal living pattern of the tenants. The average air-change rate of these houses in the preliminary phase when they were heated but unoccupied was about 2 air changes per hour at the mean wind speed, but on occupation certain modifications were made which reduced this rate; for instance, the ventilators beside the front door were blocked, and in some cases where the windows were badly fitting the worst gaps were sealed. These changes reduced the average air-change rate of the closed house to 1.5 air changes per hour.

4.2 Pressure Measurements.

The site is exposed and elevated and the average wind speed during the heating season as measured by a cup anemometer is 8.5 m.p.h. The prevailing direction is W.S.W. and is normal to the front wall of the houses; for this wind direction the pressure head developed across the houses was found to be 0.9 times the velocity head.

4.3 Air-Change Measurements.

The earlier studies on the closed unoccupied houses had shown that the air-change rate of a house could be predicted with sufficient accuracy by an equation of the form

$$R = A + Bv \quad \ldots\ldots (1)$$

where R is the air-change rate of the house in air changes per hour, A and B are two constants and v the wind speed in m.p.h. A broad interpretation of this equation in terms of the processes of natural ventilation is that A represents the air change produced by heated flues and/or stack pressure through the openings of the closed house, which are effective when the wind speed is low (this has been taken as a constant as such winds are infrequent on this site and the dependence on temperature difference was not detected). When the wind pressure is above some critical value, the air change of the house is mainly dependent on wind speed and is then predicted by $A + Bv$. A and B varied slightly from house to house, but at the mean wind (8.5 m.p.h.) the air-change rates of the houses examined were the same (2.0 air changes per hour). It seemed logical, therefore, to develop the analysis of the air-change rate of the occupied houses in terms of equations $R_1 = A_1 + B_1v$, $R_2 = A_2 + B_2v$, etc., where each equation predicts the air-change rate of any house for a specific pattern of window opening.

In the present studies, 128 air-change rates of occupied houses were obtained with the number of open windows ranging from 0 to 7 top-hung vent-lights, 0 to 2 side-hung casements and on three occasions an open front or side door. Wind speeds varied from 0 to 25 m.p.h., but the mean window opening and wind speed were not materially different from the seasonal mean for the site, so that the sample could be taken as representative of both these factors. Approximately 75 per cent. of the results were obtained from houses with 0 to 4 vents open, which represented the common winter habit of the tenants and a detailed analysis was made of these five conditions. Each of these five groups was analysed to give a predicted air-change rate in terms of wind speed in the form $R_n = A_n + B_nv$ where suffix n takes the values 0 to 4 and represents the number of vents open. These equations had significance levels better than 3 per cent. and the fit for two of the groups is shown in Fig. 1. It was desirable, however, to be able to predict the air-change rates in terms of a continuous variable rather than by such a series of discrete equations, and the level and slope of the five predicted lines indicated that a combined equation of the form $R = A + Bv + Cn + Dnv$ would meet this requirement. For each value of n this equation reduces to a linear equation in v, which is directly comparable with the five separate equations obtained above. The equation obtained was

$$R = 0.87 + 0.075v + 0.23n + 0.027nv \quad \ldots\ldots (2)$$

with a multiple correlation coefficient of 0.83 which for the number of results (96) implies a significance level of better than 0.1 per cent. The two factors n and v in the above equation accounted for nearly 70 per cent. of the observed variance in the results and the increase of residual variance due to using a composite equation instead of five separate equations was only 3 per cent.; this made little difference to the accuracy of prediction of R but simplified further analysis. There still remained 32 results with different combinations of opening of doors, vents and casement windows. Results relating to the opening of side-hung casements were inadequate for a detailed analysis of the above type, and the effect of an open casement on the air-change rate of the house was obtained by comparing the observed

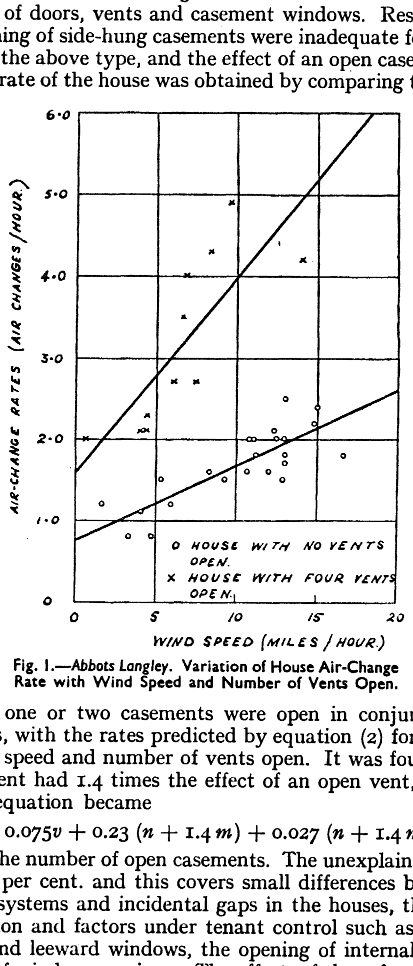

Fig. 1.—*Abbots Langley*. Variation of House Air-Change Rate with Wind Speed and Number of Vents Open.

rates when one or two casements were open in conjunction with 0 to 4 vents, with the rates predicted by equation (2) for the appropriate wind speed and number of vents open. It was found that an open casement had 1.4 times the effect of an open vent, so the full prediction equation became

$$R = 0.87 + 0.075v + 0.23\,(n + 1.4\,m) + 0.027\,(n + 1.4\,m)v \quad \ldots\ldots (3)$$

where m is the number of open casements. The unexplained variance is about 30 per cent. and this covers small differences between the ventilation systems and incidental gaps in the houses, the effect of wind direction and factors under tenant control such as the use of windward and leeward windows, the opening of internal doors and the degree of window opening. The effect of these factors may be assumed to be distributed randomly in the results obtained, and the prediction of R from the two most important variables (wind speed and number of open windows) is accurate and realistic when applied to the houses on this site.

It is of interest to interpret the equation obtained for occupied houses, $R = A + Bv + Cn + Dnv$, in terms of the processes of natural ventilation. Here again in broad terms A and B have the same significance as outlined earlier for the unoccupied closed house, but due to the larger variations introduced by occupation, the small differences in A and B from house to house were obscured and in these results A and B are assumed to be the same for each house. The increase in house air-change rate due to opening n windows is $(C + Dv)n$, where Cn may be taken to represent the effect of heated flue and/or stack pressure on the new openings, when the wind speed is low. Above some critical value of v, the air-change rate of the house is mainly dependent on wind speed, and the effect of the new openings on the air-change rate of the house is given by $(C + Dv)n$. If this interpretation is extended to equation (3), it will be seen that at the mean wind speed of 8.5 m.p.h. the ventilation rate of the closed house is 1.51 air changes per hour, and that on the average this increases by 0.46 air changes per hour on opening a vent-light and by about 0.65 air changes per hour on opening a casement window; also that when $v = 0$ and the air-change rate of the house is dependent wholly on the heated flues and/or stack pressure, the ventilation rate of the closed house is 0.87 air changes per hour and that on the average this increases by 0.23 air changes per hour on opening a light vent and by 0.33 air changes per hour on opening a casement window.

4.4 Window-Opening Habit.

(i) *Analysis of Observations.*

Since the number of windows open was an important factor in determining the air change of a house, it was essential to know what the tenant habit was in this respect. The recorded data consisted of 147 observations in 15 houses during 26 weeks of the heating season. The average number of open windows in individual houses ranged from 0.06 casements and 0.24 vents to 0.77 casements and 3.02 vents; the mean number of windows open on the site was 0.23 casements and 1.73 vents, and at the mean wind of 8.5 m.p.h. by equation (3) this gives a mean site air-change rate of 2.5 air changes per hour during occupation. Although there were large variations in window habit from house to house and from day to day, it was apparent that there was an underlying relationship between this habit and the external climate. This was examined for the site as a whole; the average number of casements and vents open during each week (obtained from an average of approximately eighty-five individual house observations) was correlated with the weekly external air temperature and wind speed. It was found that the external temperature alone accounted for over 70 per cent. of the observed variance in the number of vents and casements open and that a further 10 per cent. of the variance could be attributed to wind speed. The relationship between the number of windows open on the site with the weekly mean external air temperature is shown graphically in Fig. 2, on which the weekly mean wind speeds are also inserted. The decrease in the number of windows open as the external temperature falls is very marked; it can also be seen that some of the observed scatter is due to wind speed, the number of open windows decreasing as wind speed increases.

(ii) *Effect on Weekly Air-Change Rate.*

From the observed weekly site window openings, the weekly air-change rates of the average house on this site have been calculated

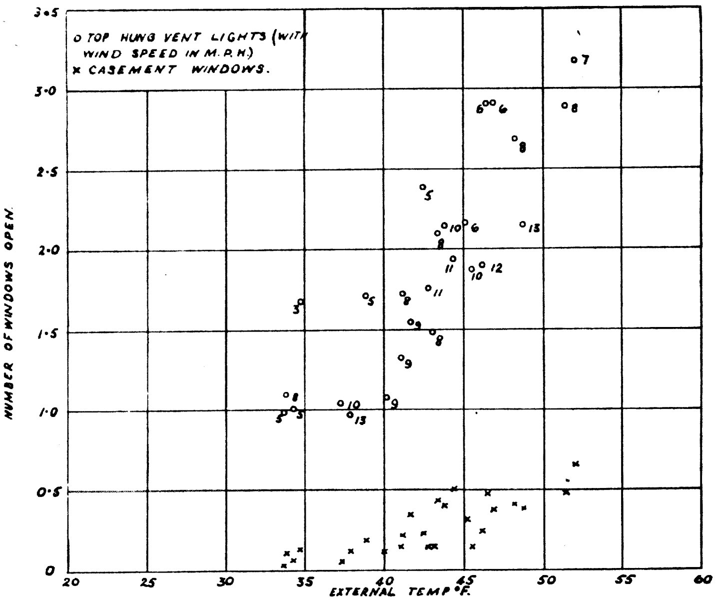

Fig. 2.—*Abbots Langley.* Effect of External Temperature on Site Window Opening.

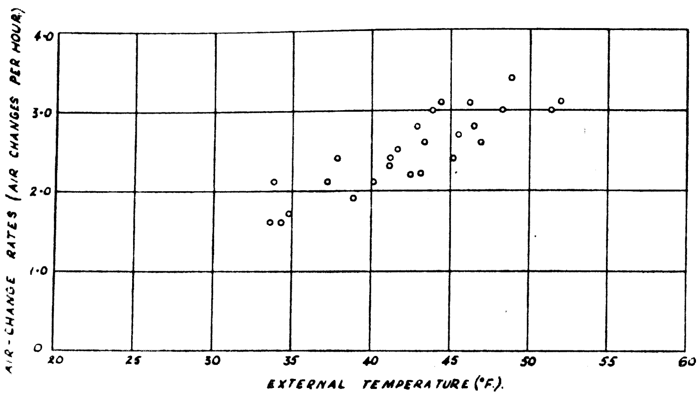

Fig. 3.—*Abbots Langley.* Effect of External Temperature on Air-Change Rates of Occupied Houses.

from equation (3) for the same 26 weeks. The variation of this air-change rate with external temperature is shown in Fig. 3—the reduction in the rate at low temperatures is due to the closing of windows.

(iii) *Effect on Weekly Heat-Loss Rate.*

It may be shown that the heat-loss rate of a house is related to its air-change rate by the equation

$$Z = 0.21 \triangle TR$$

where Z is the heat-loss rate in therms per week, $\triangle T$, the difference between a weighted house temperature and external temperature in °F., and R is the equivalent air-change rate in air changes per hour.

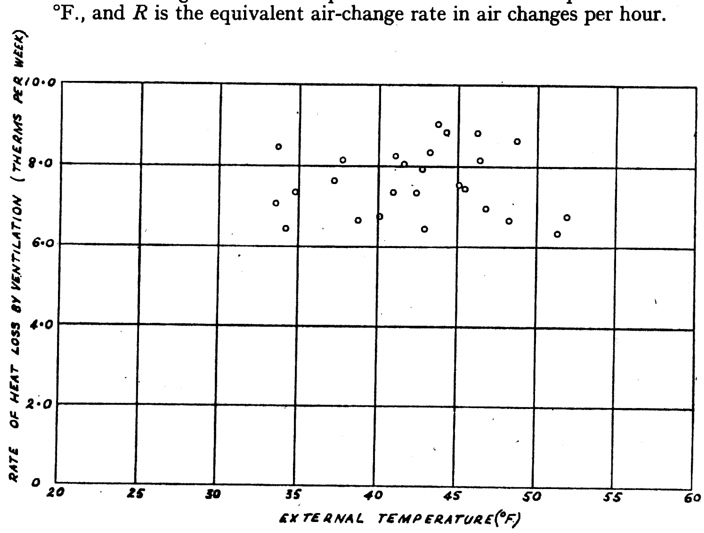

Fig. 4.—*Abbots Langley.* Effect of External Temperature on Rate of Heat Loss by Ventilation of Occupied Houses.

The variation in weekly air-change rates with temperature is not the only factor affecting the corresponding heat-loss rate. A factor of equal importance is the variation in $\triangle T$. For a house with constant internal temperature, $\triangle T$ increases by 1° F. for 1° F. fall in external temperature, but due to economic considerations, window-opening habit and in some cases the maximum output of the appliances, in practice the house temperature falls with decreasing external temperature, and on this site $\triangle T$ increases by 0.5° F. for 1° F. fall in external temperature. As external temperature drops, therefore, there is an increase in $\triangle T$ and a decrease in the air-change rate; in this set of results these two factors offset each other to a large extent and the heat loss from week to week was found to be independent of external temperature, with a mean value of 7.5 therms a week: this is shown in Fig. 4.

5. RESULTS OBTAINED ON SHELTERED SITE (BUCKNALLS CLOSE).

5.1 Introduction.

Bucknalls Close has a row of eight two-storeyed detached houses, of which the two end houses have pitched roofs and the remainder have flat roofs ; in other details the houses are similar except in the degree of thermal insulation. The line of houses is approximately north-south, and the individual houses face W.S.W. so that in relation to each other the front walls are in echelon. The heating systems in these houses consist of central heating with ceiling hot-water panels in six houses and radiators in the other two ; the boiler draws its combustion air directly from outside, so there is little interaction between the heating systems and the flow of air through the houses. The designed ventilation system allows ingress of air from outside directly through a grille into the hall ; bedrooms and living-rooms are provided with louvred openings near the doors and with ventilating shafts. The house plans correspond roughly with those at Abbots Langley, but at Bucknalls metal windows are used, and there are two extra windows due to a separate w.c. and a south window in the living-room (the south wall at Bucknalls would correspond to the party wall between the semi-detached houses at Abbots Langley). During the heating season examined the fuel used in the houses at Bucknalls was subsidised to the extent of a third of its cost.

5.2 Pressure Measurements.

The aspect of these houses is the same as at Abbots Langley, but here the ground rises slightly in front of the houses with a hedge 50 ft. away and rises sharply behind the houses to a height above that of the roofs, so that the site and the houses may be considered as sheltered. This is borne out by the mean wind speed of the site anemometer, which was 4.5 m.p.h. for the season. Pressure measurements showed that the pressure head developed across the houses for the prevailing wind was 0.4 times the velocity head.

5.3 Air-Change Measurements.

It was soon apparent that the reduced wind pressure on these houses and the absence of complicating factors such as heated flues were both tending to throw the stack effect into prominence. It has already been shown[2] that there should be a relationship between wind pressure and stack pressure which will determine which of these two factors will control the rate of air flow. The ratio of wind pressure to stack pressure for a given wind direction is proportional to $v^2/\triangle T$ where v is the wind speed in m.p.h. and $\triangle T$ the temperature difference between inside and outside in °F. When $v^2/\triangle T$ is less than some critical value and stack effect predominates

$R_{\triangle T} = E \triangle T^{\frac{1}{2}}$ for the closed house

$R_{\triangle T} = (E + Fn) \triangle T^{\frac{1}{2}}$ for the house with n windows open ;

and when $v^2/\triangle T$ is greater than this value and wind predominates then

$R_v = Bv$ for the closed house

$R_v = (B + Dn)v$ for the house with n windows open

where E, F, B and D are constants.

This critical value and the respective equations have been investigated for the three sets of results available on these houses. In the first set all windows were closed and measurements were obtained from both occupied and unoccupied houses ; in the second set, the houses were unoccupied and measurements were taken on houses with the three bedroom vents open ; the third set was obtained from houses under normal tenant occupation with a varying number of vents and casements open. To develop the equations for each set of results it was necessary to know the ranges within which the two effects obtained. This was determined empirically and the method used will be described for the first set of results. The observed air-change rates were divided by the wind speed and also by the square root of temperature difference and the quotients were plotted against log $v^2/\triangle T$. As will be seen in Fig. 5, for high values of log $(v^2/\triangle T)$, $\frac{R}{v}$ was constant and $= 0.16$, and for the remaining

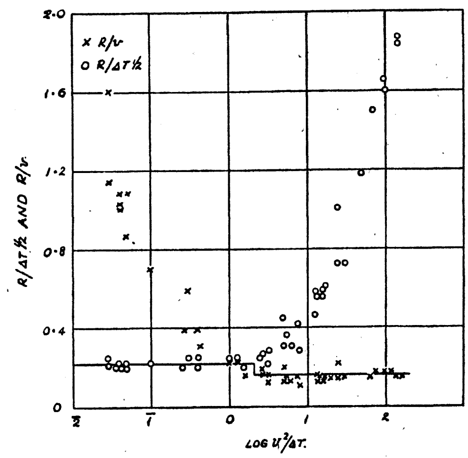

Fig. 5.—*Bucknalls Close.* Analysis of Air-Change Rates.

values $\frac{R}{\triangle T^{\frac{1}{2}}}$ was constant and $= 0.22$

thus $R_v = 0.16v$ ....(4)

and $R_{\triangle T} = 0.22 \triangle T^{\frac{1}{2}}$ ....(5)

The critical value was obtained by equating these two values of R,

$$0.16v = 0.22 \triangle T^{\frac{1}{2}} \text{ or } v^2 = 2.0 \triangle T$$

For the controlled experiments with three bedroom light-vents open the two equations were similarly

$$R_v = (0.16 + 0.21)v$$

or alternatively $R_v = (0.16 + 0.07n)v$ ....(6)

and $R_{\Delta T} = (0.22 + 0.15)\ \Delta T^{\frac{1}{2}}$

or alternatively $R_{\Delta T} = (0.22 + 0.05n)\ \Delta T^{\frac{1}{2}}$ ....(7)

and the point of change over was given by $v^2 = 1.0\Delta T$.

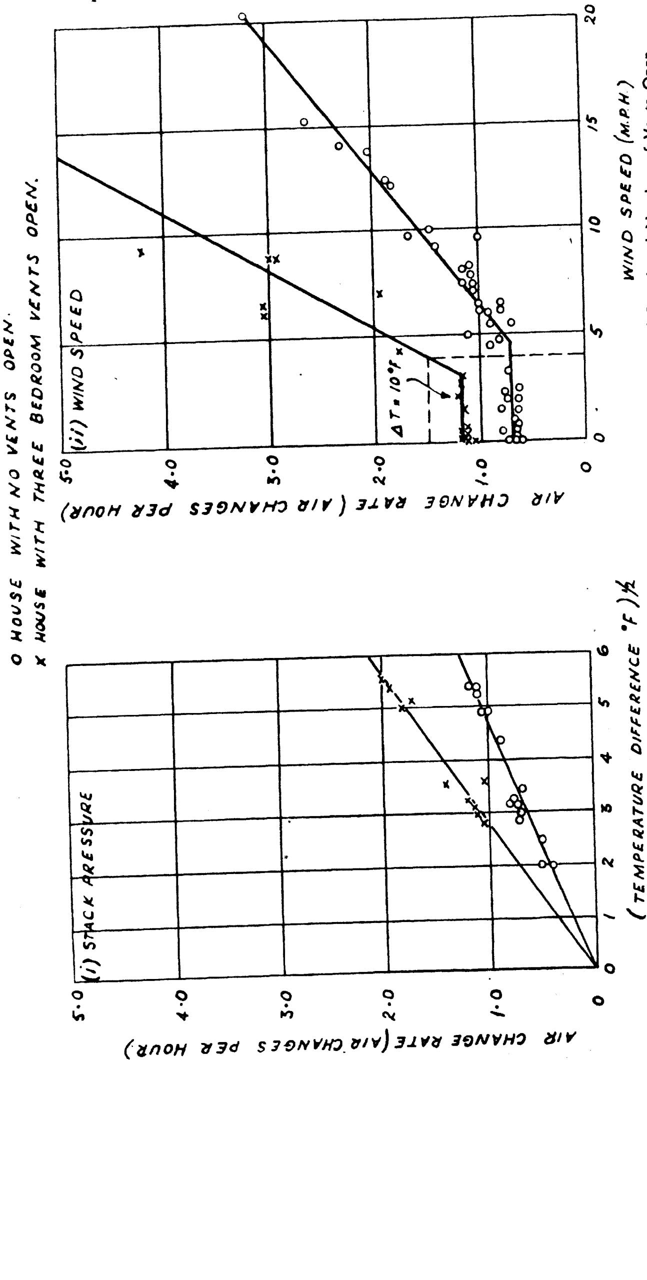

Fig. 6.—Bucknalls Close. Variation of House Air-Change Rate with Stack Pressure, Wind Speed and Number of Vents Open.

In Fig. 6 the variation of air-change rate with $\Delta T^{\frac{1}{2}}$ is shown for these two sets for those results where $v^2/\Delta T$ is below 2 for the closed house and below 1 for the house with three vents open; likewise the variation of air-change rate with v is shown for all results, but the air-change rates obtained at low wind speeds where stack pressure predominates have been corrected to a common arbitrary stack pressure (where $\Delta T = 10°$ F.).

The observed air-change rates from the third set of results when the houses were under normal tenant control have been analysed along the same lines. The number of vents open varied from one to seven, and the two equations were

$R_v = (0.16 + 0.036n)v$ ....(8)

$R_{\Delta T} = (0.22 + 0.071n)\ \Delta T^{\frac{1}{2}}$ ....(9)

The critical value of $v^2/\Delta T$ for the observed range of n's is about three.

The differences between these two equations and those obtained under controlled conditions with three bedroom vents open may be accounted for by the tenant habit regarding windows. The occupants tend to open leeward vents and in the daytime vents on the ground floor as well as the first floor; in the controlled experiments the three bedroom vents were on the first floor and with the prevailing wind one of these was windward. When v predominates, the coefficient of n may be expected to be higher in the controlled experiments due to the windward vent and when temperature difference predominates the coefficient of n may be expected to be higher in the occupied houses due to vents being open on two floors.

As at Abbots Langley, the opening of casement windows was comparatively rare and consequently few results were obtained with these open. The analysis was developed similarly and the equations obtained were

$R_v = (0.16 + 0.036n + 0.14m)v$ ....(10)

$R_{\Delta T} = (0.22 + 0.071n + 0.14m)\ \Delta T^{\frac{1}{2}}$ ....(11)

In terms of natural ventilation these equations are readily understandable. In the absence of heated flues, the house air-change rate is dependent on the effect of wind pressure or stack pressure on the openings of the house. These results may be compared with those obtained at Abbots Langley either in terms of wind pressure or stack pressure. For instance, the wind pressure corresponding to the mean wind speed at Abbots Langley is 0.032 in. w.g.; on the sheltered site a wind speed of 12.8 m.p.h. is required to give this pressure drop across the houses. From equation (10) the ventilation rate of the closed house with a wind speed of 12.8 m.p.h. is 2.0 air changes per hour and this increases by 0.46 air changes per hour on opening a light vent, and by 1.8 air changes per hour on opening a casement window. At the mean conditions of the experiments where stack pressure predominates and $\Delta T = 16°$ F., the ventilation rate of the closed house is estimated from equation (11) as 0.88 air changes per hour, and on the average this is increased by 0.28 air changes per hour by opening a vent and by 0.56 per hour by opening a casement window.

3.4 Window-Opening Habit.

(i) *Analysis of Observations.*

The observations on this group of eight houses were taken daily at random times between 09.00 and 18.00 hours from October to April by an outside observer, and these were supplemented by tenants' reports on the windows they left open at night. The variation in the individual house seasonal means was from 0.09 casements 1.36 vents to 0.73 casements 5.46 vents, and the site

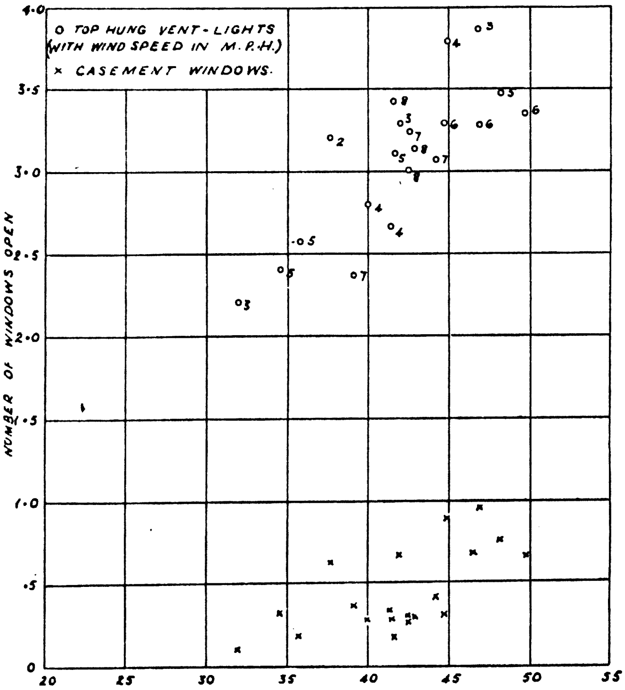

Fig. 7.—*Bucknalls Close.* Effect of External Temperature on Site Window Opening.

seasonal mean was 0.41 casements 3.06 light vents, which at the seasonal mean $\triangle T = 16°$ F. gave by equation (11) a house mean air-change rate of 2.0 air changes per hour. Here, too, the weekly average number of open windows increased with increasing external air temperature and decreased with increasing wind speed, but on this site the variation with external conditions was less marked than at Abbots Langley and the level was higher. External temperature accounted for 60 per cent. of the observed variance in the weekly number of windows open and a further 8 per cent. could be attributed to changes in wind speed. The variation with temperature is shown graphically in Fig. 7.

(ii) *Effect on Weekly Air-Change Rate.*

On this site it is more difficult to estimate the average rate over a period since the air-change rate may be at times dependent on wind speed and at other times on temperature difference. For any week there are two estimates of air-change rate based on the mean weekly wind speed and the mean weekly temperature difference. If the larger estimate is accepted and this is due to, say, v, this estimate will be too low if for any part of the week v is small and less important than $\triangle T$, so that for this period $\triangle T$ determines the air-change rate; for the same reason a weekly estimate based on $\triangle T$ may be too small. A reliable estimate of the weekly air-change rate would require for every week a mean wind speed for that part of the week when wind predominates and the mean square root of the temperature difference when stack effect predominates and as far as this experiment was concerned, such detailed information was not available.

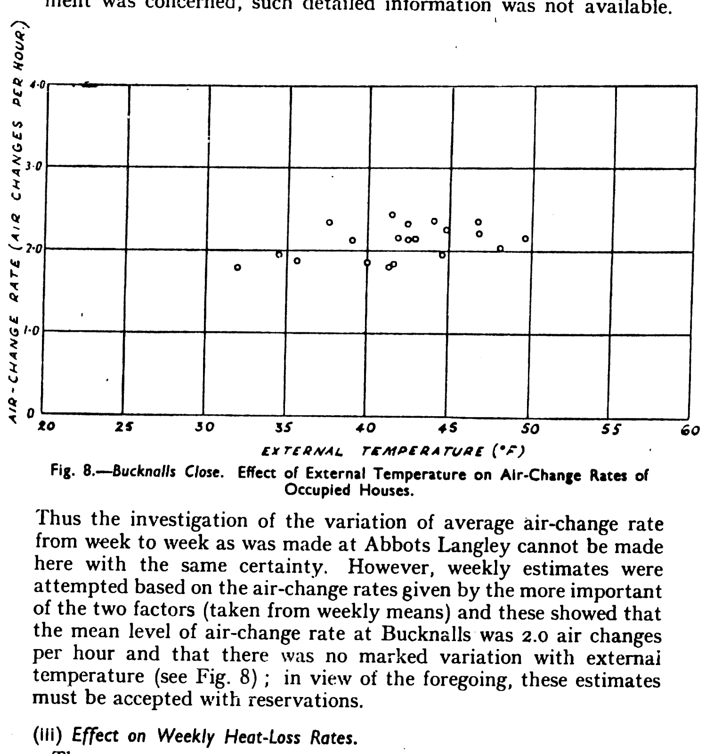

Fig. 8.—*Bucknalls Close.* Effect of External Temperature on Air-Change Rates of Occupied Houses.

Thus the investigation of the variation of average air-change rate from week to week as was made at Abbots Langley cannot be made here with the same certainty. However, weekly estimates were attempted based on the air-change rates given by the more important of the two factors (taken from weekly means) and these showed that the mean level of air-change rate at Bucknalls was 2.0 air changes per hour and that there was no marked variation with external temperature (see Fig. 8); in view of the foregoing, these estimates must be accepted with reservations.

(iii) *Effect on Weekly Heat-Loss Rates.*

The same arguments are valid in any estimate of the weekly heat-loss rates. As on the other site, the houses were not maintained at a constant temperature, and on this site the increase in $\triangle T$ for 1° F. decrease in external temperature was about 0.6° F. Once again an estimate was made of the heat-loss rates based on the weekly mean data and this gave a mean of 6.7 therms per week, but in this case the tendency was for the heat-loss to increase as the external temperature fell. This is shown in Fig. 9, where it will be seen that the range of external temperatures 50° to 30° F. covers a range of heat-loss rates from 5 to 9 therms a week respectively.

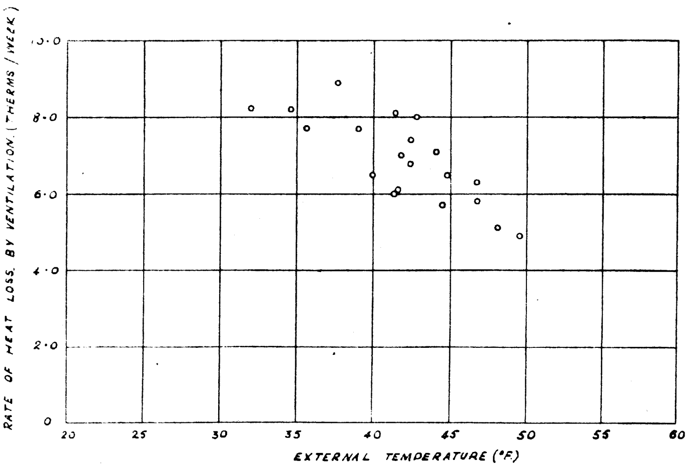

Fig. 9.—*Bucknalls Close.* Effect of External Temperature on Rate of Heat Loss by Ventilation of Occupied Houses.

6. COMPARISON OF RESULTS FROM THE TWO SITES.

A comparison of the results obtained on the two sites is summarised in the table following. It will be seen that where direct comparison is possible the results on the two sites are similar.

7. DISCUSSION.

7.1 Comparison with Other Dwellings.

Two particular sites have been examined in detail as regards air-change rate and the heat lost by ventilation. In considering to what extent these results are applicable to other dwellings, it becomes necessary to examine the expected range and influence of the factors determining the ventilation rates of heated houses.

The Ventilation System.

The ventilation systems on the two sites are not typical, but in action they are considered not to differ much from the conventional "flue or air brick" system.

The Size of Incidental Gaps Around Doors and Windows.

The houses at Abbots Langley have standard wooden windows and the external doors are weather-stripped, whereas at Bucknalls the windows are metal and the doors are not weather-stripped. It will be noted from the table that at the same wind pressure, if allowance is made for the weather-stripping, there is little difference in the overall air flow through the houses, and hence the incidental gaps on the two sites are approximately the same. In the opinion of builders who inspected the Abbots Langley site, the fit of the windows was considered typical of present-day construction: more precise information on this matter is being obtained by laboratory studies and field surveys on modern windows.

	Abbots Langley	Bucknalls Close
1. WIND PRESSURE.		
Exposure	Exposed	Sheltered
Mean seasonal wind speed ..	8.5 m.p.h.	4.5 m.p.h.
Direction of prevailing wind (W.S.W.)	Normal to house front	Normal to house front
Pressure head produced across house with W.S.W. wind ..	0.9 × velocity head	0.4 × velocity head
Pressure drop at respective mean winds	0.032 in. w.g.	0.004 in. w.g.
2. TEMPERATURE.		
Mean seasonal external air temperature	42° F.	42° F.
Mean seasonal difference between house temperature and outside	14.4° F.	16° F.
3. TENANT WINDOW - OPENING HABIT.		
Mean number of open vents (with house ranges)	1.73 (0.24 to 3.02)	3.06 (0.99 to 5.46)
Mean number of open casements (with house ranges) ..	0.23 (0.06 to 0.77)	0.41 (0.12 to 0.73)
4. AIR-CHANGE RATES (CHANGES PER HOUR).		
(*a*) For mean seasonal wind and temperature difference ..	v = 8.5 m.p.h. ΔT = 14.4° F.	v = 4.5 m.p.h. ΔT = 16.0° F.
Closed house	1.51	0.88
Increase per open vent ..	0.46	0.28
Increase per open casement ..	0.65	0.56
Occupied house with mean site windows open	2.46	1.98
Range for individual occupied houses	1.6 to 3.1	1.0 to 3.0
Increase in site rates due to occupation	0.95	1.10
(*b*) At a fixed wind pressure ..	0.032 in. w.g.	0.032 in w.g.
Closed house	1.51	2.05
Increase per open vent ..	0.46	0.46
Increase per open casement ..	0.65	1.79
(*c*) At a fixed temperature difference	Flues and/or Stack (ΔT = 14.4° F.)	Stack (ΔT = 14.4° F.)
Closed house	0.87	0.84
Increase per open vent ..	0.23	0.27
Increase per open casement ..	0.33	0.54
5. HEAT-LOSS RATES.		
Weekly site rates	7.5 therms/week	5 to 9 therms/week

The Air Flow Induced by Heated Flues.

The present experiments offer little information on the air flow induced by heated flues since on the sheltered site at Bucknalls, where such air flow might have been important, there are no heated flues to draw air from the houses and at Abbots Langley the effect has been swamped by wind.

The Magnitude of the Wind Pressure.

The wind pressure on a building depends on the free wind speed and the shelter afforded by nearby trees and buildings and the surrounding terrain. The free wind in inland areas in Britain during the winter averages about 10 m.p.h. (e.g. Abbotsinch 7.9 m.p.h., Cranwell 10.8 m.p.h., Manchester 11.8 m.p.h., Croydon 10.5 m.p.h.).[4] The full velocity head of this wind is about 0.05 in w.g., but there will be a variation in this head with aspect and a pressure head of 0.04 in. w.g. is probably more typical of houses on an exposed site. The pressure will be reduced if the houses are shielded by nearby buildings or trees, and in towns also by the reduction in the free wind speed due to the drag of the buildings on the flow of air.[5] The shielding effect of adjacent buildings was investigated on the model scale by Bailey and Vincent.[6] They found that the shielding effect of one building on an adjacent one of similar size was dependent on the distance apart of the two buildings; the pressure drop across the sheltered house becomes 50 per cent. of the full wind pressure when the distance apart is three times the width of the buildings and decreases to zero when the distance apart is 1.5 times the width; below this distance the pressure drop reverses and has a magnitude up to 30 per cent. of the full wind pressure. There is little information on the cumulative effect in an extensively built-up area, but measurements by Bedford[7] of wind speeds at street level in such areas indicate the probable reduction. He found that the wind speed in London streets corresponding to a free wind at Kew of 5 m.p.h. was 1.8 m.p.h. and 4.1 m.p.h. when the Kew value was 20 m.p.h. For a closely built-up area, a mean effective wind speed of 3 m.p.h. is a reasonable figure and the pressure corresponding to this is 0.005 in. w.g. Thus the wind pressures found on the two experimental sites are at the extremes of the probable values.

The Magnitude of the Stack Pressure.

The stack pressure depends on the extent to which the air inside a house is heated above the external temperature. A recent survey of temperatures in local authority houses conducted by the regional officers of the Ministry of Fuel and Power has shown that the average temperature difference maintained during the heating season in houses with modern thermal insulation standards is about 14° F., so the differences of 14° F. and 16° F. observed on the two experimental sites are fairly typical. Thus for similar two-storeyed dwellings the stack pressures will be the same as in the experimental houses.

Window-Opening Habit.

During the temperature survey referred to above the opportunity was taken to observe the window-opening habit. The mean opening observed for the season were 2.64 small and 0.71 large windows, where the sizes were similar to the vent-lights and casements on the two experimental sites. The number of small windows lay between the two observed figures for Abbots Langley and Bucknalls, but the number of large ones was slightly higher. Since the survey was conducted in and near large towns it might be expected that the observed figures would be similar to those obtained on the sheltered site, viz., Bucknalls, and the agreement here is reasonable. The survey also showed that in cold weather the tenants reduced the number of windows open, but the effect was not as clearly defined as in the restricted but more exhaustive investigation on the two sites.

7.2 Increase of Air-Change Rate Due to Occupancy.

During the heating season the average increase in the air-change rate of the two groups of houses due to occupancy was found to be 0.9 and 1.1 air changes per hour; the consistency implies that the difference in level of window opening on the two sites tends to compensate for the difference in exposure. An estimate of the increase in air-change rate in the local-authority houses of the regional survey due to the mean observed opening of 2.64 small windows and 0.71 casements has been made on the basis that the pressures on these sites would correspond to those at Bucknalls; with the observed temperature difference of 14° F., the increase in air-change rate due to occupation is 1.1 air changes per hour. For similar houses the increase due to occupancy of one air change per hour during the heating season may be taken as generally applicable.

7.3 Heat Loss by Ventilation in Occupied Houses.

The weekly rates of heat loss of the occupied houses on the two sites have been examined in relation to the most important of the climatic factors, external temperature; they could similarly be examined with respect to wind or possibly temperature difference. There is, however, a single parameter which contains the effects of these climatic factors and this is the heat-loss rate for the closed house corresponding to the weeks under consideration; the use of this parameter allows for the effects of different exposures so that the two sets of results become comparable when referred to this single factor. The ranges of the weekly heat-loss rates for the closed houses are from two to five therms per week on the sheltered site, and from three to six and a half therms per week on the exposed site; there is, therefore, a region of overlap of three to five therms per week. It was found that in this region the rates of the occupied houses were similar and averaged about seven and half therms per week, representing an increase of three and half therms per week over the corresponding rates of the closed houses. In view of this agreement, the results from both sites have been combined and arranged in equal groups based on the rank order of the corresponding heat-loss rates of the closed house. The grouped mean heat-loss rates of the occupied houses have been plotted against the corresponding heat-loss rates of the closed houses in Fig. 10. It will be seen that for values of the heat-loss rates of the closed houses below five therms a week, the effect of occupancy has been to increase the

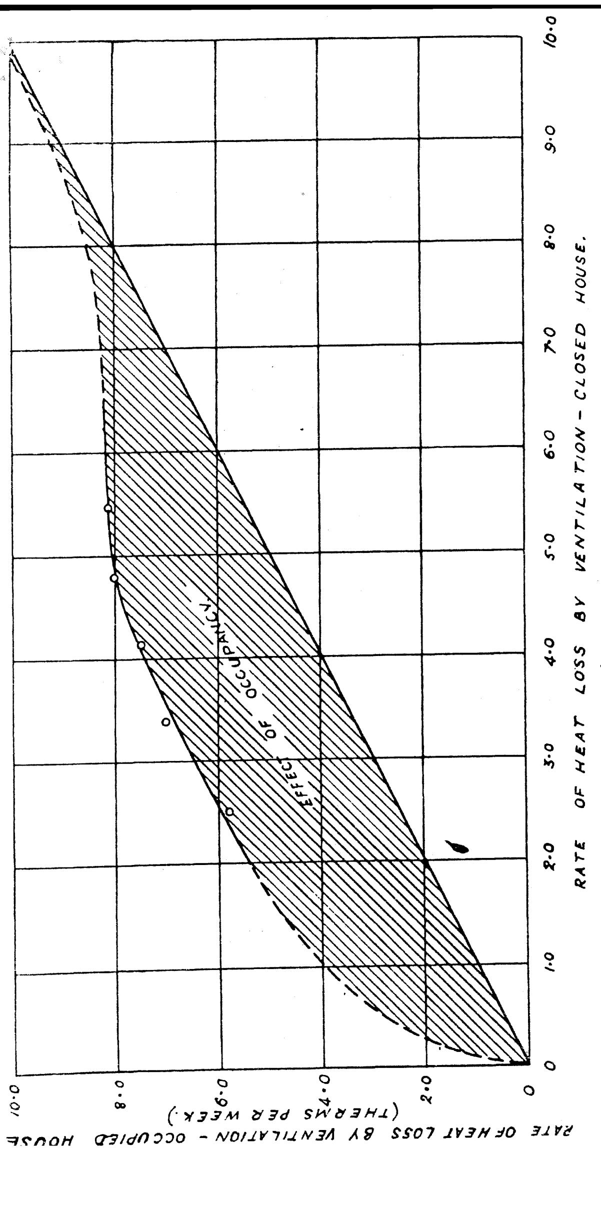

Fig. 10.—*Abbots Langley and Bucknalls Close.* Effect of Window Opening Habit of Occupants on Rate of Heat Loss by Ventilation.

heat-loss rates by about three therms per week ; for values of the heat-loss rate of the closed houses between five and eight therms per week (corresponding to increasing severity of external climate), occupants close windows so that the total heat-loss rate remained constant at approximately eight therms per week. Above a heat-loss rate of eight therms per week from the closed houses (when conditions may be considered extreme), open windows will be rare and the heat-loss rates of the occupied houses will approximate to those of the closed houses, and increase as the rates of the closed houses increase.

From the discussion of the factors involved in ventilation (paragraph 7.1), the range of the heat-loss rates for the closed houses on the two experimental sites may be taken as typical of those to be expected on sheltered and exposed sites. Therefore, it follows that the increase of heat-loss rate due to occupancy of houses on a sheltered site would be about three therms per week and that as the site becomes more exposed this increase would be progressively reduced and the rate of heat loss by ventilation would become approximately constant at about seven or eight therms per week.

7.4 Ventilation and the Domestic Heating Load.

The regional survey of temperatures maintained in dwellings showed that during the heating season houses with modern insulation standards were heated to an average of 14° F. above the external temperature. If the houses at Bucknalls, rather than those at Abbots Langley, are taken as typical of modern housing (inasmuch as the doors are not weather-stripped), the corresponding air-change rate of a closed house on a sheltered site would be 0.82 per hour and the rate of heat loss by ventilation would be 2.4 therms per week. The corresponding rate of heat loss for the average occupied house, as given by Fig. 10, is 5.7 therms per week.

On exposed sites the increased heat loss by ventilation tends to reduce the temperature difference between inside and outside, and it has been estimated that the observed average temperature difference of 14° F. (which refers mainly to suburban areas) will be reduced to 13° F. on an exposed site. When the houses at Bucknalls are exposed to wind pressures typical of those of an exposed site the average air-change rate is 2.1 air changes per hour. This involves a heat loss of 5.7 therms per week by ventilation, increasing to 8.2 therms per week when the houses are occupied.

As already pointed out, the present experimental work yields little information on the air flow induced by heating appliances. The extent of this is being investigated in complementary laboratory studies. The effect will be greatest in sheltered houses, especially where there is an open fire which may extract as much as 6,000 cu. ft. of air per hour. The consequent increase in the ventilation of the house is estimated to be 3,000 to 4,000 cu. ft. per hour, which is an increase of 0.5 air changes per hour or an additional heat-loss rate by ventilation of 1.5 therms per week. On an exposed site, however, an open fire would draw more of its air requirements from the normal flow of air through the house due to wind, and this would involve a smaller increase in the air-change rate.

Summing up, it is estimated that the heat loss by ventilation during the heating season for a house similar to those at Bucknalls when occupied by an average tenant ranges from 6 to 7 therms per week on a sheltered site, and averages about 8 therms per week on an exposed site. Generally, the rate of heat loss may be expected to be between 6 and 8 therms per week, depending on exposure and heating system; these figures correspond to a seasonal heat loss by ventilation of 190 to 270 therms, and imply house air-change rates of between 2 and 3 per hour according to the exposure and the heating system.

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D A U

ULTRA-VIOLET DEODORISATION OF AIR*

By W. SUMMER, D.Sc.(Tech.), F.Inst.E., A.Inst.P., M.Amer.Phys.Soc.†

Synopsis.

The chemical nature of odours and the function of the olfactory and gustatory senses are discussed. The sense of taste enhances the offensiveness of an obnoxious odour. Odours can either be masked or destroyed. Only destruction is really effective. The aim of deodorising by destruction is to change the molecular structure of the offensive substance so that new structures are formed that have no stimulating effect on the mucous membranes of the average human nose. The two most effective methods available to industry are chlorination and oxidation. The most potent form of the latter method is ozonisation. The advantage of the process of generating ozone by means of ultra-violet radiation is discussed from both the physicist's and the ventilating engineer's aspects. Design data for practical installations are given and methods and models discussed. Physiological effects are briefly mentioned, and a number of installations are used to illustrate the various points of the text.

Chemical and Physiological Aspects of Odours

ONE of the fundamental constituents of a molecule is the radical. This is a group of atoms which, though essential to every chemical combination, remains unchanged itself.

The presence of certain radicals gives a definite colour to the compounds of which they are a part and these radicals are termed chromophores, i.e. colour carriers.

Other radicals act differently in that they provoke, for instance, a sensation of taste (gustaphores), or a sensation of smell (osmophores). Some of the osmophoric radicals are:

$=CO$	carbonyl
$-CHO$	aldehyde
$-COOH$	carboxyl
$-OH$	hydroxy
$-CH_2OH$	carbinol
$-SH$	sulph-hydryl.

A sensation is the final result of the interaction of two related principles, in this case of the osmophores of the causative substance and of the osmoceptors which are certain physiological structures in the mucous membrane of the nose.

The organ of smell is the nose. It is one of the simpler sense organs. The ventilating engineer's interest in the nose is not only based on the fact that it is the critic of his actions, but also that it is the unsurpassed detector of odours.

Each gas has a characteristic olfactory threshold, i.e. a lower limit of stimulation.

The case of methyl mercaptan CH_3SH deserves particular mention, because it is the substance with the lowest threshold value known. It is sufficient for 4.10^{-8} mg. per l., i.e. 3 parts of methyl mercaptan to be present in 10,000,000,000,000 parts of air in order to be perceptible to the average sense of smell. This means that a sensation of methyl mercaptan will not be elicited unless, at least, one thousand molecules of the substance are available per inspiration to stimulate each cell in the nasal mucosa.