EXPERIMENTAL STUDIES

IN

NATURAL VENTILATION

OF

HOUSES

by

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INSTITUTION OF HEATING AND VENTILATING ENGINEERS

REPORT

SESSIONAL MEETING, LONDON, NOVEMBER 16th, 1949.

A SESSIONAL Meeting of the Institution was held at the Institution of Mechanical Engineers, Storey's Gate, London, S.W.1, on Wednesday, November 16th, 1949. The President, Mr. H. H. Bruce, occupied the Chair.

There were about 65 members and visitors present. The following signed the attendance register :—

Members.—Messrs. A. C. Mann, H. L. Perry, L. Copeland Watts, J. K. Stead, D. H. Ingall, T. C. Angus, D. G. Lewis, J. W. Stitson, S. W. Hutt, A. A. Old, A. W. Maxlow, A. G. Paine, W. F. Moore, G. R. Jackson, C. D. Fox, R. Duncan Wallace, M. Berry, E. W. Wilton, E. B. Tanner, G. N. Cramp (London) ; G. W. Case (Kenton) ; J. C. Weston, N. S. Billington (Watford) ; H. L. Egerton (Ruislip) ; G. E. Middleton (Cambridge) ; I. F. James (New Malden).

Visitors.—Messrs. H. Batley, D. R. Wills, A. G. Stork, Merlin S. Jones, J. S. Hales, F. Grieve, R. J. Newman, P. B. Adams, A. B. Adams, L. L. Hughes, W. J. Harton, D. E. Hickish, L. M. Croton, D. Turner, F. A. Chrenko (London) ; G. D. Nash, A. T. Pickles, W. A. Thomas, K. A. Hoskin, A. Whittaker, D. J. Petty, J. W. L. Hindey, G. Burnand, M. Alos, J. M. Dowdall, T. W. Heppell, P. T. Loader (Watford) ; A. S. Manhlarz (Bromley) ; H. S. Crump (Margate) ; S. G. Crawford (Wilts) ; K. E. Johnson (Colindale) ; H. R. Hill (St. Albans) ; P. A. Coles (Colinbrook).

The President, in introducing Mr. J. B. Dick, who was to present a paper on " Experimental Studies in Natural Ventilation of Houses," said that Mr. Dick was a Senior Scientific Officer at the Building Research Station, Watford. He had been carrying out experiments on the measurement of air flow through buildings, and several members of the Institution, on a recent visit to Watford, had seen some of that work in progress.

Mr. J. B. Dick introduced his paper by discussing the fundamental laws of ventilation which underlay the experimental studies*. He developed the laws along the lines proposed by Shaw†, i.e. by assuming that the air flow through ventilators and cracks around windows was proportional to the square root of the acting pressure and that, therefore, the components could be regarded as equivalent to thin plate orifices whose areas could be calculated. Mr. Dick pointed out that the assumed type of flow was not universal, but

Continued on page 465

*We hope to publish a fuller account of this introduction in a future issue of the *Journal.—Editor.*

†W. N. Shaw, " Air Currents and the Laws of Ventilation," Cambridge University Press, 1907.

in his opinion it was a good approximation and provided the means to examine in some detail the ventilation processes in a house.

He then proceeded to discuss the laws of flow when components were in series or parallel and demonstrated these laws using a model house. He used a fan to simulate the effect of wind on a house and showed how the pressure drops across the walls were related to the areas of openings in the walls. He then briefly discussed the typical values of the acting pressures and the equivalent areas of the components in houses, and related these to the results of his experimental studies.

Mr. Dick concluded by showing how the laws could be applied to some typical problems. His first example was concerned with the operation of air-bricks and he showed how excessive the flow through one could be at even moderate wind speeds. He suggested that a much more satisfactory method for ventilating flueless rooms would be to use a ventilator which terminated in a ventilated roof space, in this way obtaining an operation similar to that of a flue. In his second example, he discussed the air flow induced by an open fire. The rate of flow was frequently excessive and Mr. Dick showed how it might be reduced by weather-stripping doors and windows but pointed out that this might involve a risk of smoking. He thought that the real solution lay in the design of the appliance as a whole to give satisfactory burning with a reduced throat area and reduced air flow, and added a plea for the provision of a damper to control the flow when the pull was excessive.

EXPERIMENTAL STUDIES IN NATURAL VENTILATION OF HOUSES*

By J. B. DICK, M.A., B.Sc., A.Inst.P.
Building Research Station.

SESSIONAL MEETING, LONDON, NOVEMBER 16th, 1949.

Synopsis.

Experimental studies in the natural ventilation of houses are described. These were made in four similar houses with different ventilation systems constructed for large-scale trials on house heating at Abbots Langley. Measurements were made of the rates of air change in rooms and the air flow between rooms by using a tracer-gas technique, and of the acting aeromotive forces due to wind and temperature differences.

It is shown that the variations in the measured rates of air change could be attributed mainly to changes in wind speed, and that the direction of the wind and the magnitude of the temperature differences were secondary factors. The analysis is extended to estimate the rate at which air leaves the houses and the consequent rate of heat loss by ventilation ; these rates are given as linear functions of wind speed. The relationships between the measured pressure differences and the speed and direction of the wind are discussed, and it is shown that the observed results are in fair agreement with those obtained by other investigators in experiments with models.

The estimates of the rates of air flow are used with the results of the pressure measurements to estimate the rate of air flow through the windows for a known pressure, thus effecting an in situ calibration of the fit of the windows.

1. INTRODUCTION.

The experiments described below are concerned with the ventilation of 20 experimental houses at Abbots Langley, Herts. During the winter of 1947-48 these houses were subjected to a large-scale heating experiment designed to give factual data on the performance of a large number of heating appliances varying from open fires to central heating. The background to these trials has been described recently,[1] and full descriptions and results of the first phase of the experiment (when the houses were unoccupied) have been published [2, 3, 4]. In brief outline, these houses were run with doors and windows shut for a winter by laboratory staff who simulated the demands of a family of two adults and two children on the heating systems and who read the temperatures attained and fuel consumed. In order to assess the efficiency and the economic aspects of the various types of systems, it was essential to know the heat lost by ventilation. A series of tests was made to provide this information and at the same time a study was made of the air movement within the houses, the rates of air change of individual rooms and pressure distributions across walls.

It was recognised at the outset of the experiment that it would not be possible to investigate in detail the ventilation characteristics of every room in the 20 houses, and it was, therefore, decided to concentrate the air-change measurements on three houses, each representative of one of the main types of heating and associated ventilation systems, and to obtain only representative measurements in the remaining houses. The detailed measurements were later extended to a fourth house where the rates were noticeably lower than in other houses with the same type of system.

2. DESCRIPTION OF HOUSES AND VENTILATION SYSTEMS.

The 20 experimental houses are semi-detached and are built in two parallel rows facing west-south-west as shown on the site plan in Fig. 1. The site itself is flat and, except for a row of semi-detached houses on its eastern fringe, unsheltered by trees or buildings. The

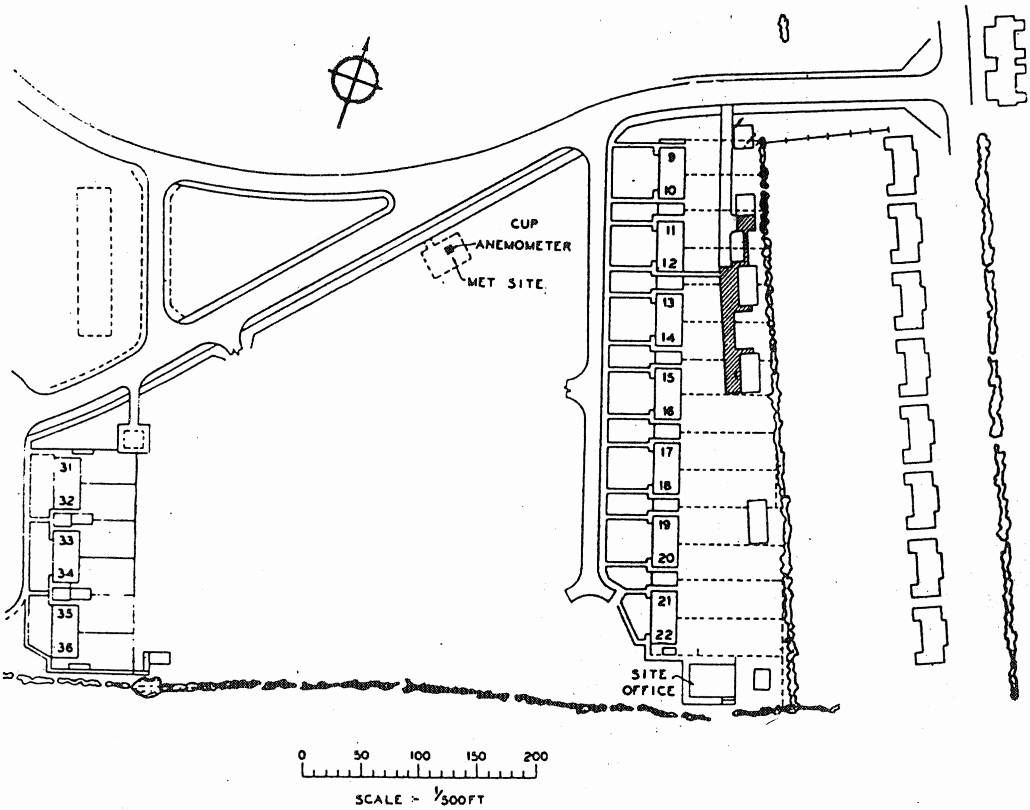
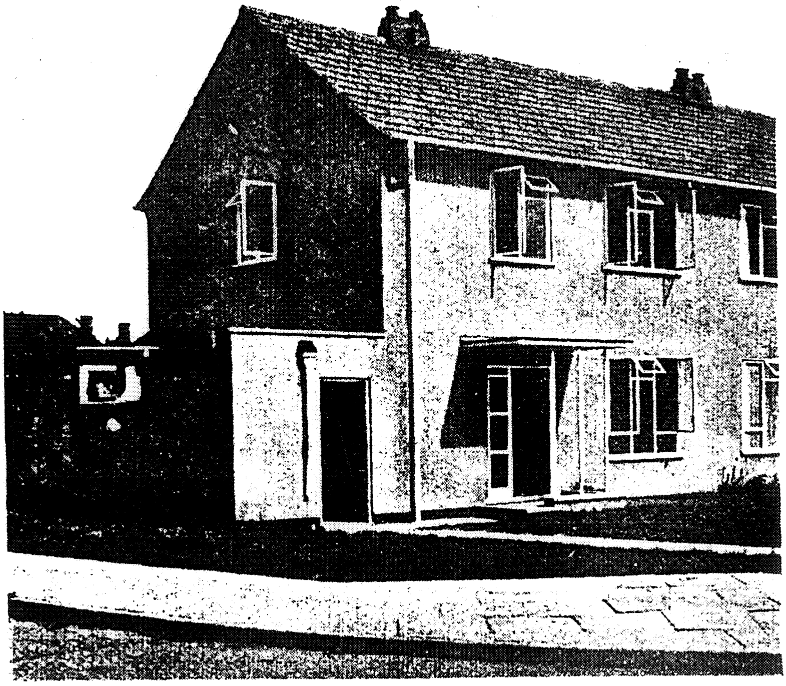


Fig. 1.—Site Plan.

front and back elevations of the houses are shown in Figs. 2*a* and 2*b*. The height of the houses to the eaves is 17.5 ft., and to the ridge 26.5 ft., the roofs having a pitch of 35°. There is a curtain wall 8 ft. high between adjacent houses, and this with the front wall of the houses forms in effect a continuous wall from end to end of each row. Plans of ground and first floor are shown in Fig. 3. The area of the houses is 925 sq. ft., and the volume is approximately 7,000 cu. ft. The volumes of the rooms are :—Bedroom 1, 1,025 cu. ft., Bedroom 2, 920 cu. ft., Bedroom 3, 520 cu. ft., Hall and Landing, 1,080 cu. ft., Living-Room 2,035 cu. ft., Kitchen 1,090 cu. ft., Bathroom 375 cu. ft. The ground floors are of solid construction.

In the houses there are 19 heating systems which have been fully described in a recent report by Eve and Weston[2], who have classified the different systems into three categories based on their space-heating requirements, called " partial ", " two-stage ", and " whole-house " heating. In the " partial " heating group the living room is heated by a form of open fire or stove and the remainder of the

(a)



(b)

Fig. 2.—Front and Back Elevation showing Windows Open.

house is unheated apart from any heat gained from water heating or cooking appliances; in the "two-stage" group, background heating is provided throughout the house and topping-up during periods of occupancy; in the "whole-house" group full central heating is provided.

The ventilation systems in the individual houses have been designed with reference to the heating systems installed, the basic principle of design being that for habitable rooms, i.e. the living

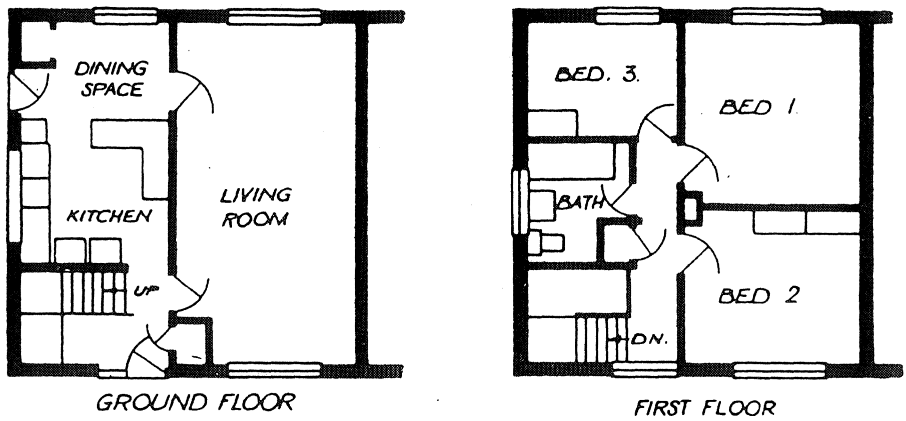


Fig. 3.—House Plan.

room and bedrooms, there should be provision both for entry of replacement air (tempered if possible) and removal of the contaminated air. Thus the replacement air for a room without convection ducts or ducts from outside is obtained through a ventilator with louvred plates 12 in.×3 in. above the door to the hall, which in turn has a similar ventilator beside the front door. The contaminated air from a room may leave either through a flue, or in flueless rooms through a ceiling ventilator and duct to the roof space; the ducts from the bedrooms are 12 in.×2½ in., those from the living-rooms are 12 in.×4 in. The kitchen and bathroom are ventilated directly with outside, the kitchen through two air bricks in the larder and a flue and/or duct to roof space, the bathroom by an air brick. Illustrating these principles, Table I shows the ventilation systems of houses 10, 13 and 33 which belong to the "two-stage", "whole-house" and "partial" groups respectively.

The roof spaces are ventilated by allowing the soffit of the eaves to stand a little clear of the fascia, and air entering here may leave through the vents in the cement flue cap. Metal flues from solid fuel appliances lead into circular holes at the top of the caps. Flues from gas fires terminate at various levels in the roof space; the flues from living-room appliances are 8 in. diameter, those from the kitchen are 6 in. diameter for solid-fuel appliances and 4½ in. for gas appliances, and from bedrooms with gas fires there are 6 in. diameter flues.

The windows of the houses conform to British Standard sizes and types. They are single glazed and both the openable types are of two sizes, a long hinged sash 21 in.×49 in. or 21 in.×43 in., and a top hung hopper light 21 in.×12½ in. or 21 in.×10½ in.; the openable windows at front and back are shown in Figs. 2*a* and 2*b*

Table I.—Details of Ventilation Systems.

House No.	Type of Heating	Details	Bedroom 1	Bedroom 2	Bedroom 3	Hall	Living-room	Kitchen	Bath
10	"Two-stage"	Heating system	Convection. duct from L.R fire. Gas fire	As B1	As B1	Flueless gas convector	Closeable fire	Gas water heater	Towel-rail
		Air intake	Convection duct	As B1	As B1	Nil	Duct from outside, terminating beside fire	Air bricks (Larder)	Air brick
		Air outlet	Flue	As B1	As B1	Nil	Flue	Flue	Air brick
13	"Whole-House"	Heating system	Hot-water radiator	As B1	As B1	Hot-water radiator	Hot-water radiator	Magazine-fed boiler	Towel-rail
		Air intake	Vent from hall	As B1	As B1	Vent beside front door	Vent from hall	Air bricks (Larder)	Air brick
		Air outlet	Vent to roof space	As B1	As B1	Vents to B1, B2, B3, and L.R.	Vent to roof space	Flue and surrounding duct	Air brick
33	"Partial"	Heating system	Gas fire	As B1	Nil	Nil	Open fire	Domestic boiler	Towel-rail
		Air intake	Vent from hall	As B1	Vent from hall	Vent beside front door	Vent from hall	Air bricks (Larder)	Air brick
		Air outlet	Flue	As B1	Vent to roof space	Vents to B1, B2, B3, L.R.	Flue	Flue and surrounding duct	Air brick

The total length of cracks around openable windows is 74 ft. at the front, 43 ft. at the side and 92 ft. at the back. Some troubles were experienced with the fitting of the windows, mainly due to the difficulty of obtaining seasoned timber and the fact that the windows were installed during the dry summer of 1947. Warping subsequently appeared, and the remedy applied was to fit two latches rather than the more usual one to every long hinged sash. A number of builders and joinery manufacturers who have visited the site have stated that the fit achieved is now not noticeably different from that found in most house building to-day.

Similar troubles were found with the external doors where gaps were conspicuous, but in this case no such simple remedy could be applied. As the designed ventilation systems, which included such features as entry grilles beside the front door, would have been appreciably affected by the gaps around the door, it was decided to weather-strip all external doors. This was done using a phosphor-bronze strip applied on the jambs and the soffit of the lintel ; along the sill a metal threshold was run which interlocked with a metal bar screwed to the base of the door, the exterior face of which had been rebated.

3.0. AIR CHANGE AND LEAKAGE MEASUREMENTS IN ROOMS.

3.1. Experimental Procedure.

The technique which was adopted in these experiments to measure air-change rates was that first used by Marley[5] : a tracer gas (usually hydrogen) is introduced into a room, mixed thoroughly with the air in the room, and the subsequent concentration is then measured using a katharometer and recording galvanometer. If c_0 is the initial concentration of tracer gas in the room, then the concentration c at time t is given by

$$c = c_0 e^{-yt}$$

where y = rate of air change (generally air changes per hour). If there is good mixing between the replacement air entering the room and the air in the room, then the rate x at which air enters and leaves the room is given by

$$x = yV$$

where V is the volume of the room. A fuller description of the method and the instrumentation is given in the Appendix.

Early experiments indicated that the decay rates recorded by katharometers placed in different parts of the same rectangular rooms showed little variation, so in the case of these rooms, a single katharometer placed centrally was considered adequate to measure the air-change rate. In the irregular space comprising the entrance hall, stairs and landing, preliminary tests had shown that the rates measured varied according to the position of the katharometer ; this variation was reduced by using a slow-running fan placed half-way up the stairs and directed into the blind space in the well of the stairs. This reduced the time lag of mixing between the entrance hall and the landing without affecting the flow through any apertures, and the air-change rate in the total space was then taken as the mean of the two rates measured by katharometers placed in the entrance hall and landing.

Before starting air-change measurements in a house the air-flow pattern was determined ; ammonium chloride was used as a smoke tracer to determine the direction of flow and a hot-wire anemometer to measure the speed. Flows through cracks around windows and doors, vents between rooms and to roof space, convection ducts, flues and air bricks were examined. These factors were then recorded on a plan of the house with the corresponding external wind speed and direction ; in the event of any significant change of wind during the air-change measurements, the air-flow pattern was redetermined.

In those rooms where the air-flow pattern showed that the air leaving the room passed directly to outside and not through any adjoining room, the air-change rate was measured by introducing sufficient hydrogen to give an initial concentration of 0.3 per cent. and then recording the decay of the tracer in the room for a period of 15-30 minutes ; a fan was used to ensure good mixing of the hydrogen as it was introduced, but it was then switched off for the decay measurements. For those rooms where the air leaving the room went partly to outside and partly to adjacent rooms, the room was sealed completely from the adjoining rooms until the beginning of the decay measurement. Simultaneous records of the decay of concentration of hydrogen in the injected room and the rise in concentrations in the adjacent rooms were then taken. The Appendix shows how such measurements may be used to separate the air flow from these rooms into the component which flows through cracks in the door to adjacent rooms and that component which passes directly to outside through flues, ventilators in ceilings or window cracks.

For each experiment, the following readings were taken :—

(*a*) Air-flow pattern within the house.

(*b*) Internal and external temperatures.

(*c*) Internal and external relative humidities.

(*d*) State of heating appliances in the house.

(*e*) External wind speed and direction as recorded by a cup anemometer in the standard meteorological enclosure on the site. These were subject to wide fluctuations even in the relatively short interval of time of these experiments. There were eight automatic counters, which registered the number of counts of the anemometer in each of the eight direction sectors, north, north-east, east, south-east, south, south-west, west, north-west, and one counter registering the total number or counts irrespective of direction. Readings were taken at the beginning and end of each experiment and counts covering four directions were not infrequent. The total number of counts over this period gave the average wind speed, and the average direction in degrees was taken by weighting each direction for its number of counts, and equalising the moment about the mean direction. The convention for wind direction used in these experiments was to measure the angle (θ°) made by the mean wind direction with the normal to the front of the house, θ being measured round the detached side of the house (0 to 360°).

3.2. Results.

3.2.1. *The Operation of the Ventilation Systems.*

The adequacy of the ventilation systems is to some extent shown by the rates of air change in the rooms, which are given in section 3.2.2, but, particularly in the centrally-heated houses which have arrangements for internal flow between rooms, the pattern of air flow is also of interest as it reveals how fresh the replacement air is. In the centrally-heated houses, it was found that with the predominant wind (which is on the front of the house) air entered through the grille at the front door and then passed through the grilles above the internal doors to the living-room and bedrooms 1 and 3; on the other hand, air entered bedroom 2 through the cracks around the windows and part of this then passed through the grille above the door into the hall. With the wind on the back of the house these flows were reversed. Thus generally the back bedrooms and the living-room did receive a supply of tempered air from the hall, but this was not necessarily fresh as air from the front bedroom passed into the hall. It will be shown later that with the predominant wind the air entering the house through the grille at the front door was only a fraction of the total entering the house, and thus the action of the ventilation system was to some extent nullified in the case of the living-room.

3.2.2. *Air-Change Rates in Rooms.*

The process of air change in a room is produced by a complex pattern of forces due to the impact of wind and to temperature differences between internal and external air columns. These forces act on the network of air resistances (formed by the flues, cracks around windows and doors, etc., in the house), and thus the magnitude and direction of the air flow through the individual resistances is determined not only by the acting pressures, but also by the magnitudes of the resistances elsewhere in the network. In other words, a room in a house cannot be considered as an isolated entity with characteristics of its own, but is linked, to a greater or lesser degree, with the remainder of the house. It is thus extremely difficult to predict on theoretical grounds the air-change rate in a room of a house for particular values of variables such as wind (speed and direction) and temperature difference. The observed rates have consequently been examined with reference to simple cases of the effects of these variables. In this analysis the results from houses with ventilation systems similar to those in houses 10, 13, and 33 have been included with those of the corresponding room; the results in house 19 which were significantly lower than those measured in house 13 (with its similar system), have been analysed separately.

The aeromotive force in a heated flue of a particular appliance may be expected to remain fairly constant, and thus if it were the only force causing air change in a room, the air-change rate (Υ) could be represented by the equation:

$$\Upsilon = \text{constant}$$

The rate of air-flow through ventilators, windows, etc., is approximately proportional to the square root of the acting pressure, and as wind pressure is proportional to the square of the wind speed, the rate of flow is proportional to wind speed. Thus if wind were the only source of pressure, the equation for the air-change rate could be written :

$$Y = \text{constant}.\ v, \text{ where } v = \text{wind speed.}$$

Similarly stack effect by itself would induce an air-change rate given by :

$$Y = \text{constant } (\Delta T)^{\frac{1}{2}}, \text{ where } \Delta T = \text{difference between internal and external temperatures.}$$

The orders of these aeromotive forces during the experimental work were :

Heated flue (mean excess temperature 100° F. in flue 27 ft. long) = 0.07 in. w.g.

Wind (velocity head at mean wind speed of 8.5 m.p.h.) = 0.04 in. w.g.

Stack effect (room on ground floor—15 ft. column with temperature excess 20° F.) = 0.01 in. w.g.

In the first examination of the results, no allowance for stack effect or wind direction was made and the observed rates of air change in each room were used to determine the appropriate constants A and B in a prediction equation of the form :

$$Y = A + Bv$$

where Y = air-change rate (per hour) and v = wind speed in m.p.h. Thus in effect the linear correlation between air-change rate and wind speed was examined. The form of equation includes the two special cases when wind and heated flue act separately. In its present application the constant A can also include the smaller effects due to heated flues in adjacent rooms, and the result of stack effect which becomes more pronounced at low wind speeds.

Significant correlation between the air-change rates and wind speed was found in 22 of the 28 equations applicable to the rooms of the four houses : the significance levels varied from 5 per cent. to less than 0.1 per cent. The correlation coefficients obtained ranged from 0.57 to 0.91 so that the percentage of the variance in the observed air-change rates which could be attributed to changes in wind speed ranged from 33 to 83 per cent. Typical examples of the relationship between air-change rates and wind speeds are shown in Fig. 4 which shows the results obtained in the living-rooms of houses 13, 33 and 10. There is no heated flue in the living-room of house 13 and here there is a marked increase of air-change rate with wind speed ; the living-room of house 33 has an open fire and ventilators to hall and hence outside, and here the increase of air-change rate with wind speed is lower ; whilst in the living-room of house 10 which has a heated flue and under-floor duct from outside, external wind speed has very little effect on the ventilation rate, and the relationship is only significant on the 10 per cent. level.

It was noted that in some cases there was a considerable variation of air-change rate with wind direction, and in particular that rooms on the windward side of the building had higher rates than those on the leeward side. A form of mathematical analysis was applied to determine whether there was any significant change in the rates for wind directions normal to the four sides of the house. The regression equation used was of the form :

$$Y = A + Bv + Cv \cos \theta + Dv \sin \theta$$

where θ = the angle between the normal to the front of the house and the wind direction ; for each house it is measured from the normal around the detached side of the house.

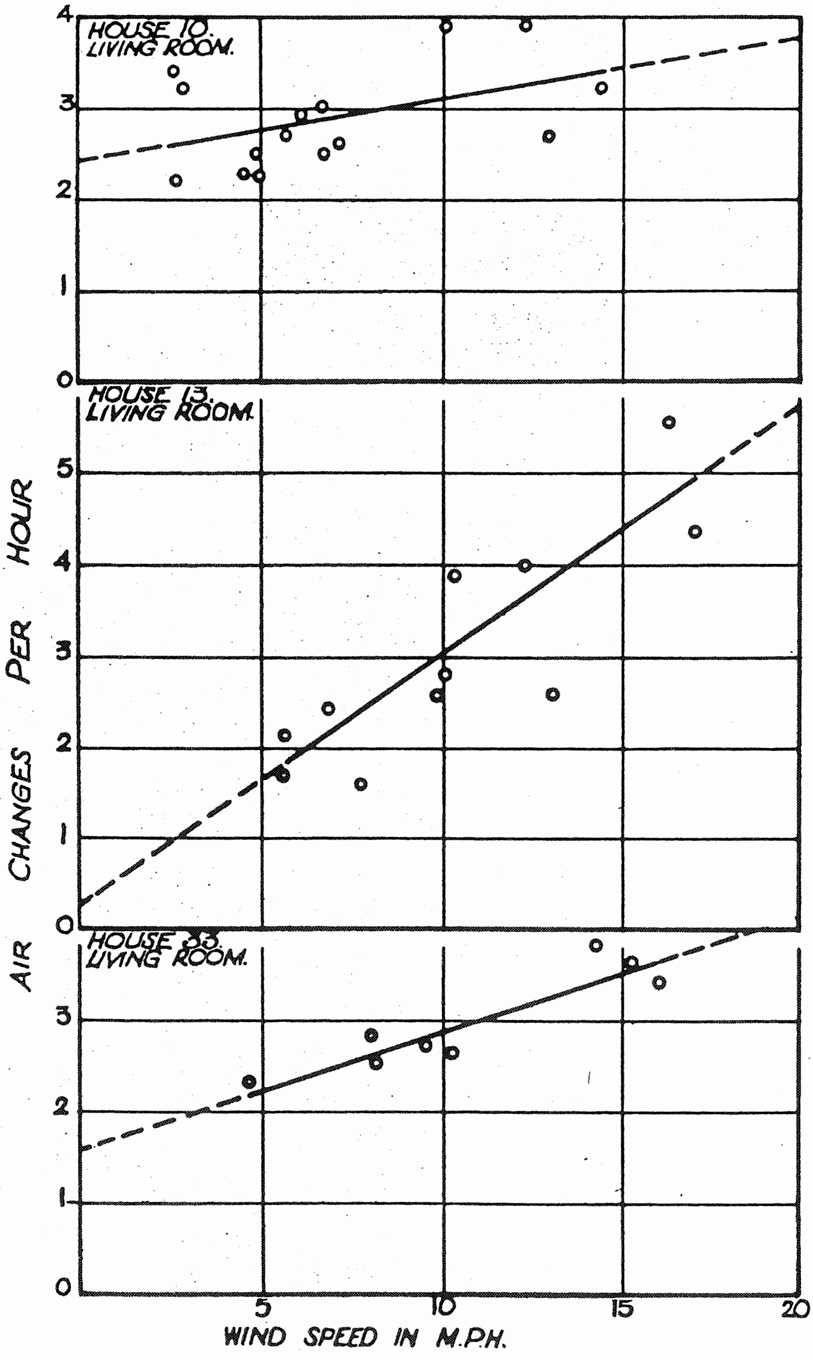


Fig. 4.—Variation of Air Change Rates in Living-rooms with Wind Speed.

A, B, C, D = constants to be determined from the experimental data.

In effect the term $Cv \cos \theta$ takes account of any difference in air-change rate for east and west winds ($\theta = 180°$, $\theta = 0°$) and the term $Dv \sin \theta$ any difference for north and south winds.

It was found that the addition of these terms significantly reduced the residual variance in a number of cases : a 5 per cent. significance level was again adopted when examining the reduction of residual variance. For instance the results obtained for bedrooms 1 and 2 of house 10 (which are of approximately equal volume) gave a prediction equation for the air-change rate :

$$Y = 0.8 + 0.21v \pm 0.10v \cos \theta$$

the sign of the cosine term being different for the two rooms, so that the air-change rate of the room on the windward side was higher than that on the leeward side by 0.20 $v \cos \theta$. The directional effect was also pronounced in the hall of 13 which has a ventilator at the front door, where the addition of the direction terms increased the significance of the regression equations from the 2 per cent. level (correlation with v only) to better than the 0.1 per cent. level. In all there were 10 sets of results where the addition of the directional terms significantly reduced the residual variance remaining after the correlation with wind speed only ; the multiple correlation coefficients now ranged from 0.75 to 0.95, and thus the percentage of the observed variance which was now accounted for ranged from 56 to 90 per cent. There was also one set in which the correlation with wind was only significant when the directional terms were used.

There remained 5 sets of results out of the 28 in which no significant correlation could be found using the above forms of equation. These included the living-room of house 10 (which with its heated flue showed a correlation which was only significant on the 10 per cent. level), the hall of house 10, and 3 bathrooms. The reason for the insignificance of the correlation is not the same in all these cases. It may be due either to some factor other than wind controlling the air-change rate or to inadequacy of the chosen forms of equation to represent the action of the forces involved. For instance, the results for the living-room in house 10 show a lower variance than those obtained in the bathrooms, and comparison of the coefficients of variation showed that this difference is significant on the 5 per cent. level ; in the former case the effect of the heated flue predominates and thus swamps the effect of wind, in the latter case the lack of correlation is due to the complexity of the acting pressure patterns not being adequately represented by the chosen forms of equation.

The residuals, after the above correlations had been completed, were examined for the effects of temperature difference between room and external air and of humidity. No relationship was detected.

The estimated rates in the rooms of the four houses for mean wind speed (8.5 m.p.h.) and direction during the period of measurement are shown in Table II, which also gives the air-change rates based on the standards in the Egerton report and standard errors of the estimates. The average standard deviation of the observed air-change rates about the prediction equations was of the order of 0.7 per hour, which with the number of observations obtained (an average of 14 per set) implied a standard error of estimate of about 0.2 air changes per hour. It will be seen from the table that the standard errors of estimate are lower in house 19 than in the other

Table II.—Average Ventilation Rates and Comparison with Egerton Standards.

	Room volume (cu. ft.)	Bedroom 1 1,025	Bedroom 2 920	Bedroom 3 520	Hall 1,080	Living-room 2,035	Kitchen 1,090	Bath 375
	Standard air supply (cu. ft. per hour)	1,200	1,200	600	—	2,400	1,000	—
	Equivalent air changes per hour ...	1.17	1.30	1.16	1.00	1.18	0.92	2.00
House 10	Average air changes per hour	2.4	2.8	1.2	2.3	2.9	3.3	1.9
	Difference from standard	+1.2	+1.5	0	+1.3	+1.7	+2.4	−0.1
	Standard error of estimate	0.31	0.31	0.36	0.21	0.13	0.33	0.32
House 13	Average air changes per hour	2.0	2.5	3.1	4.3	2.6	3.5	4.3
	Difference from standard	+0.8	+1.2	+1.9	+3.3	+1.4	+2.6	+2.3
	Standard error of estimate	0.17	0.26	0.15	0.20	0.26	0.14	0.33
House 33	Average air changes per hour	Same as House 13				2.7	Same as House 13	
	Difference from standard					+1.5		
	Standard error of estimate					0.07		
House 19	Average air changes per hour	1.1	2.2	1.2	4.6	1.4	3.0	2.4
	Difference from standard	−0 1	+0.9	0	+3.6	+0.2	+2.1	+0.4
	Standard error of estimate	0.08	0.17	0.08	0.28	0.06	0.13	0.13

three houses ; this is partly due to the increase in variance in the results shown for the three houses caused by including results from comparable rooms in other houses (where the fit of windows will vary), and also to the increased number of observations in house 19, where about 20 results were obtained in each room.

It was found that the difference in ventilation rates between rooms in houses 19 and 13 was due to differences in the fit of the windows. For instance, the living-room windows in house 13 were found to have an average crack of about 0.09 in., whereas comparable measurements in house 19 gave a figure of about 0.05 in. It will be shown later that a large proportion of the air entering these houses does enter around the cracks, and that, therefore, for the predominant wind the above measurements do indicate the order of the effects.

It was remarked earlier that the exterior doors were weather-stripped. Before this was done sufficient air-change measurements were obtained to enable the effect of weather-stripping to be shown, although insufficient results were obtained to formulate prediction equations applicable to all rooms. Fig. 5 shows the effect of weather-stripping the external doors on the air-change rates on some rooms of these houses—the kitchens of houses 13 and 33, the living-room of house 33, and the hall of house 10 (which in its weather-stripped condition is an example of a set of results where no significant correlation was found).

3.2.3. *Air-Change Rates for Houses.*

In the analysis of the heating experiment it was desired to form prediction equations for fuel consumptions in terms of the relevant variables (such as wind speed and difference between internal and external temperatures) and for this purpose it was necessary to know whether the rate of heat loss from a house by ventilation could be adequately expressed as a linear function of wind speed or whether the addition of directional terms was necessary. It has been shown that the air-change rate of a room could in general be adequately expressed by an equation of the form :

$$Y = A + Bv$$

although in some cases the use of an equation of the form :

$$Y = A + Bv + Cv \cos \theta + Dv \sin \theta$$

significantly improved the accuracy of the prediction equation ; the question now asked was whether the rate at which heat was lost from the houses did vary with the direction of the wind. Before examining the variation of rate of heat loss with direction of wind, the simpler case of the variation of rate of air change of the houses with wind direction will be discussed.

The air-change rate of a house considered as a whole is obtained by considering the rate at which air enters or leaves the house : it should be noted that it cannot be obtained simply by summing the rates of air flow as estimated for individual rooms, as all the air entering or leaving a room does not necessarily come directly from or pass directly to outside. In the present analysis the air leaving each room has been separated by the method outlined in the Appendix into that going to the remainder of the house and that

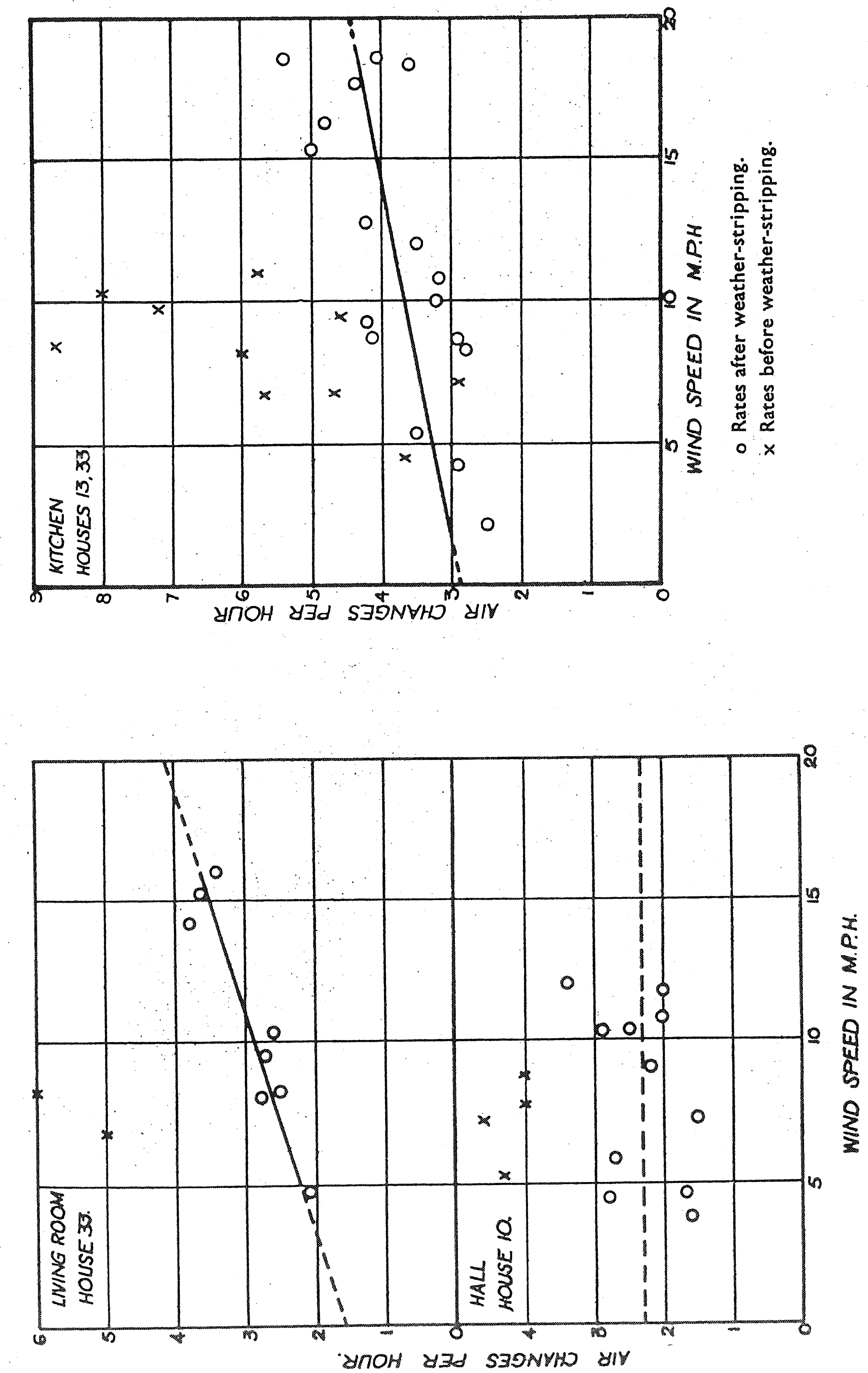


Fig. 5.—Examples of Reduction of Air-Change Rate by Weather-stripping External Doors.

going outside, and by summing the latter throughout all rooms, the rate of air flow from the house has been estimated for winds of varying direction.

In detail, the fraction (F) of the total air flow through a room which represented air passing directly to outside was plotted against wind direction on a polar diagram, and it was assumed that F was independent of wind speed over the measured range. An example of this type of polar diagram is given in Fig. 6, which shows the

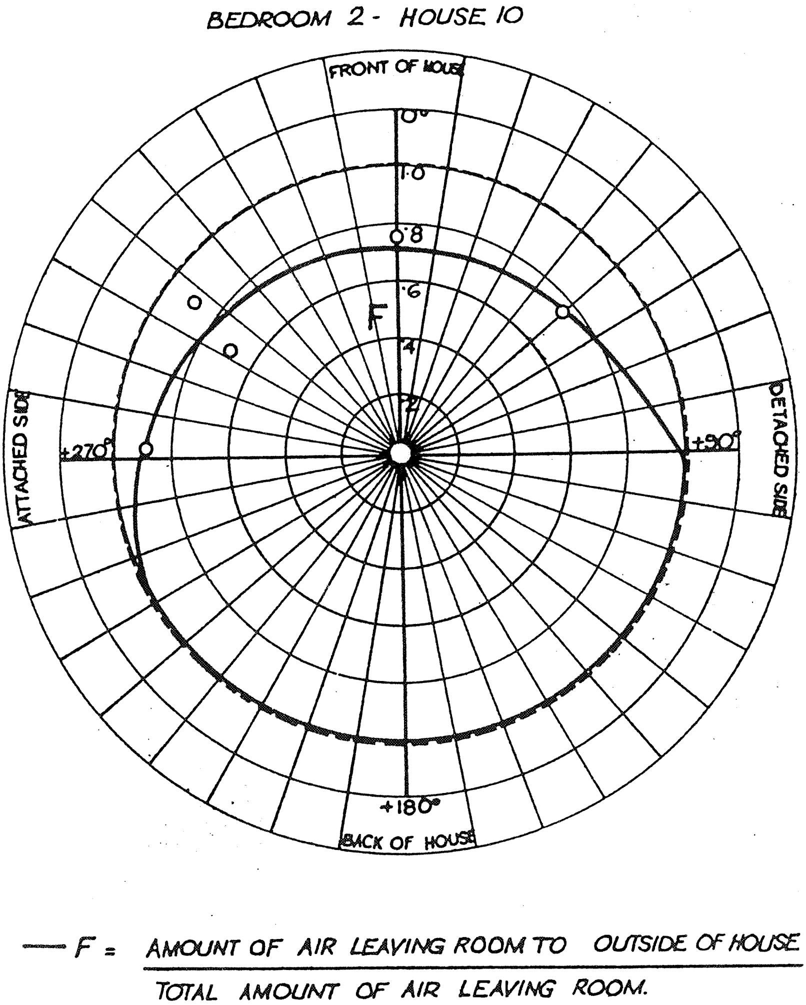


Fig. 6.—Example showing Variation of F with Wind Direction.

measured values of F for bedroom 2 in house 10 plotted against θ, and also the line which has been drawn to estimate F as a function of θ. Thus for instance with the wind on the front of the house ($\theta = 0°$) about 0.72 of the air leaving the room passes directly to outside, and with the wind on the back of the house ($\theta = 180°$) all the air leaving the room goes directly outside. Now the air-change rate for this room has already been shown to be

$$Y = 0.8 + 0.21v + 0.10v \cos\theta \text{ air changes per hour}$$

so that the rate at which air enters or leaves the room is given by :

$$V\,(0.8 + 0.21v + 0.10v \cos\theta) \text{ c.f.h.}$$

where V = volume of room in cu. ft.

Hence using this equation and the polar diagram for F as a function of θ, the rate at which air leaves the room may be expressed as a linear function of v for any particular direction by substituting the corresponding values of F and θ in the expression,

$$FV\,(0.8 + 0.21v + 0.10v\cos\theta).$$

Reverting to our example, the appropriate expressions for this room for $\theta = 0°$ and $\theta = 180°$ are

$$0.72\,V\,(0.8 + 0.21v + 0.10v) \text{ i.e. } 0.72\,V\,(0.8 + 0.31v)$$

and $$1.00\,V\,(0.8 + 0.21v - 0.10v) \text{ i.e. } 1.00\,V\,(0.8 + 0.11v)$$

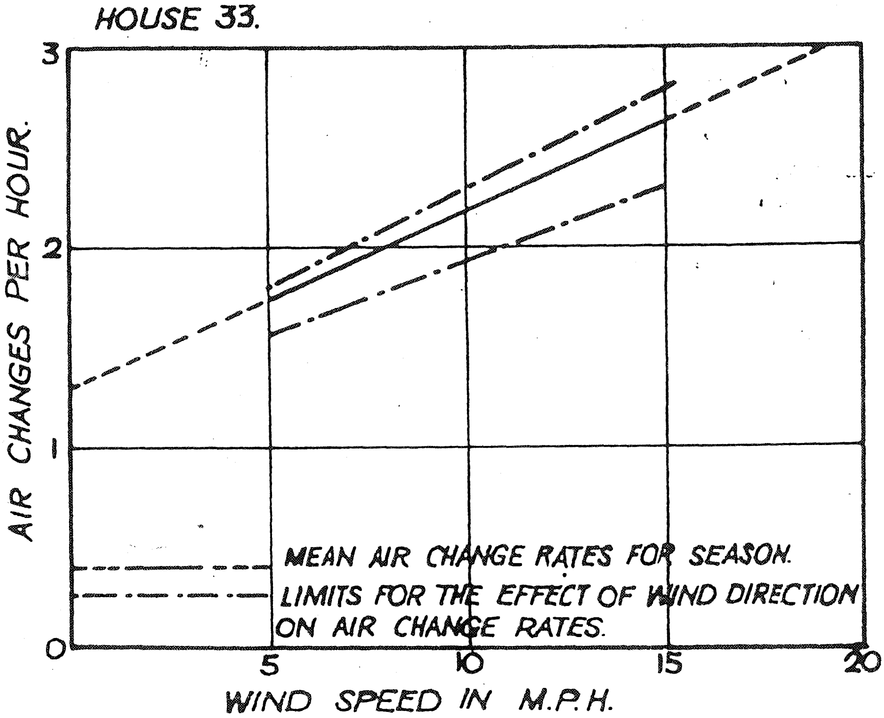


Fig. 7.—The Effect of Wind Speed and Direction on Air-Change Rate of a House.

In the present calculation, the rate of air loss to outside from each room was estimated as above for winds with directions at intervals of 45° ($\theta = 0°, 45°, 90° \ldots$) and the linear equations obtained for the individual rooms for each direction were then summed throughout the house. This estimate of the total rate of air flow into or from the house divided by the volume of the house then gave the air-change rate for the house as a function of wind speed, there being eight equations for the eight chosen directions. Fig. 7 shows the range of variation in the air-change rates of house 33 for the eight directions for wind speeds between 5 and 15 m.p.h. It will be seen that wind direction plays a relatively unimportant part in determining the air-change rate of a house, the directional terms of the rooms tending to cancel out when summed together (witness bedrooms 1 and 2 in house 10 with equal and opposite directional terms in the air-change rate equations). Comparison of the effect of wind direction on the air-change rates of the three houses indicates that houses with heated flues are less affected than those without, the range of variation increasing from house 10 to house 33 to house 13.

From the frequency of the wind counts in each direction during the experimental period, weighting was applied to the eight equations obtained for the different directions for each house and the weighted mean equation determined. This equation gave the best estimate of the air-exchange rate of the house expressed as a function of wind speed and independent of wind direction. The equations for these mean rates are given in Table III together with the estimated rates at the mean wind speed of 8.5 m.p.h.: no undue significance should be attached to the identical estimates for houses 10, 13 and 33 at $v = 8.5$ m.p.h.—the order of the rates is similar, but the exact agreement in this instance is fortuitous. The results from house 19 which were calculated from room rates measured in subsequent tests are given for comparison.

Table III—Rates of Air Change in the Houses.

House No.	Air changes per hour	Air changes per hour at $v = 8.5$ m.p.h.
10	$0.99 + 0.120\,v$	2.0
13	$1.03 + 0.117\,v$	2.0
33	$1.29 + 0.088\,v$	2.0
19	$0.63 + 0.075\,v$	1.3

Insufficient results were obtained before the external doors were weather-stripped to enable the full prediction equations for the air-change rates of the rooms to be developed. The effect of weather-stripping has, therefore, been estimated from a comparison of the air-change rates at corresponding wind speeds before and after weather-stripping; as far as possible the comparison has been made at the mean wind speed of 8.5 m.p.h. and where this has not been possible it has been assumed that the ratio of the air-change rates before and after weather-stripping does not vary with wind speed.

The air-change rates for the three houses before and after weather-stripping are given in Table IV for the mean wind speeds.

Table IV—The Reduction of Air Change Rate by Weather-stripping External Doors

House No.	Air changes per hour before weather-stripping	Air changes per hour after weather-stripping
10	2.6	2.0
13	2.5	2.0
33	3.3	2.0

3.2.4. *Rates of Heat Loss from the Houses by Ventilation.*

We have seen in section 3.2.3. how the rate at which air passes from a room to outside may be estimated for any direction of wind in terms of wind speed. Similarly by multiplying this loss rate by the temperature difference between room and external air, and then by the specific heat of air, the rate at which heat is lost from the room by ventilation may be estimated, and then progressing as before the total rate of loss of heat from each house may be estimated.

This calculation was made for each house using the mean temperature differences between the room and external air during the experimental period. The limits of the effect of wind direction on the rate of heat loss in therms per week are plotted for house 33

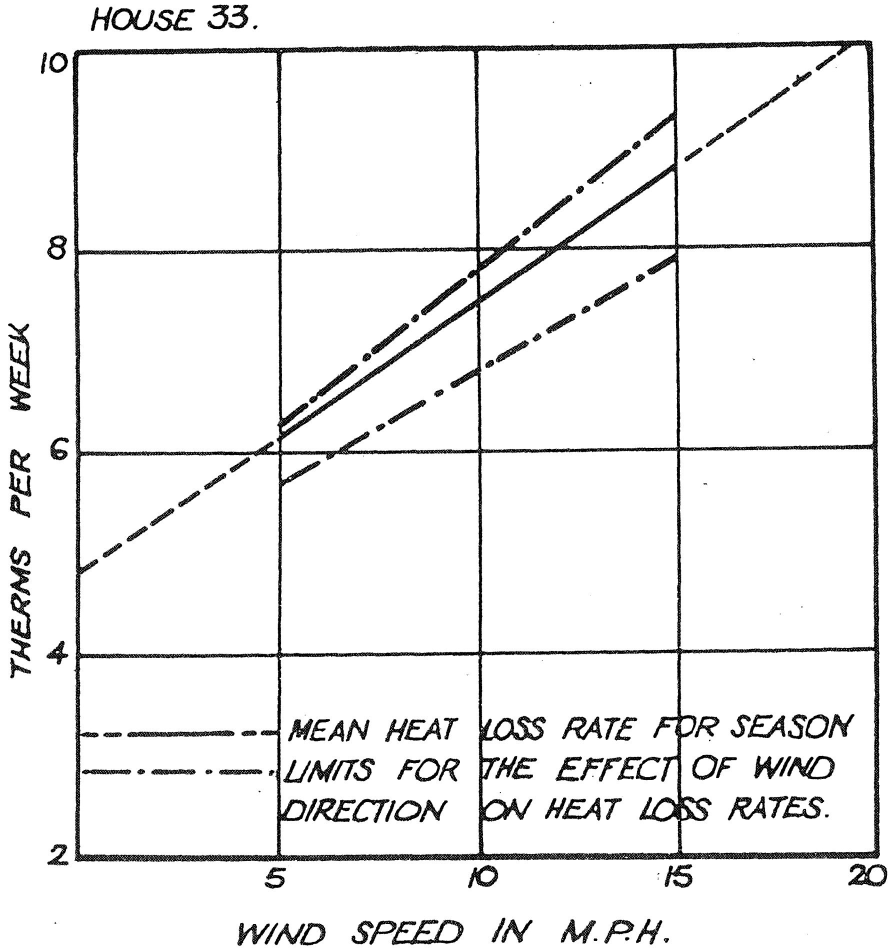


Fig. 8.—The Effect of Wind Speed and Direction on the Rate of Heat Loss by Ventilation of a House.

in Fig. 8. Again the variation with wind direction is small and therefore the weighted equation for each house allowing for the frequency of the observed directions has again been calculated. These equations are given in Table V and it will be seen that the average loss from the houses was about 8 therms per week.

Table V.—The Rate of Heat Loss from the Houses by Ventilation

House No.	Rate of heat loss (Therms per week)	Rate of heat loss at $v = 8.5$ m.p.h. (Therms per week)
10	$3.77 + 0.422\ v$	7.4
13	$4.77 + 0.471\ v$	8.8
33	$4.82 + 0.270\ v$	7.1

The temperatures in the houses during the trials were not the same, and to enable a comparison to be made, the above calculation has been extended to give the heat loss rate per °F. temperature difference between the house mean and the external temperature ; as will be seen from the results in Table VI the average rate of heat loss was about 0.5 therm per week per °F.

Table VI—The Rate of Heat Loss from the Houses by Ventilation per °F. Excess

House No.	Mean excess temp. (°F.)	Rate of heat loss (Therms/week/°F.)	Rate of heat losss at $v = 8.5$ m.p.h. (Therms/week/°F.)
10	16.1	$0.23 + 0.026\ v$	0.45
13	18.2	$0.25 + 0.026\ v$	0.48
33	13.7	$0.35 + 0.020\ v$	0.52

These estimates of the rates of heat loss per °F. were obtained using the mean temperature excess of the individual rooms during the experimental period. The rate of heat loss per °F. at a particular time may differ from the above due either to a change in the temperature distribution throughout the house or an interaction between the heating load and the ventilation rate—an effect which was not detected during the present measurements but was probably obscured by the variance between houses. The effect of a change in temperature distribution was determined by recalculating the heat loss rate per °F. using the temperatures observed on the coldest and warmest days during the experimental period. The two equations obtained agreed closely with the original equations for the same house : the three equations applicable to house 33 are shown in Fig. 9.

4.0. PRESSURE MEASUREMENTS.

4.1. Details of Experiment.

The pressure measurements were made in and around house 19, which is a centrally-heated house with ventilation system similar to that in house 13, as described in Table I. During the pressure measurements the heating system was in operation and maintained a temperature differential of about 14° F. To simplify the measurements the internal doors were kept open, but external doors and windows were closed.

The external pressure on a window was made available for measurement by passing a ¼ in. copper tube through the centre of a mullion of the window, the end of the tube being flush with the external surface. As model experiments by other workers had indicated that there could be appreciable variations of pressure over a wall (particularly when the wall is to the windward side) these tubes were fitted in all the main windows of the house ; a further tube was led into the roof space so that the pressure drop in the ventilation ducts could be examined. The pressure differences between external surfaces and across windows were then measured

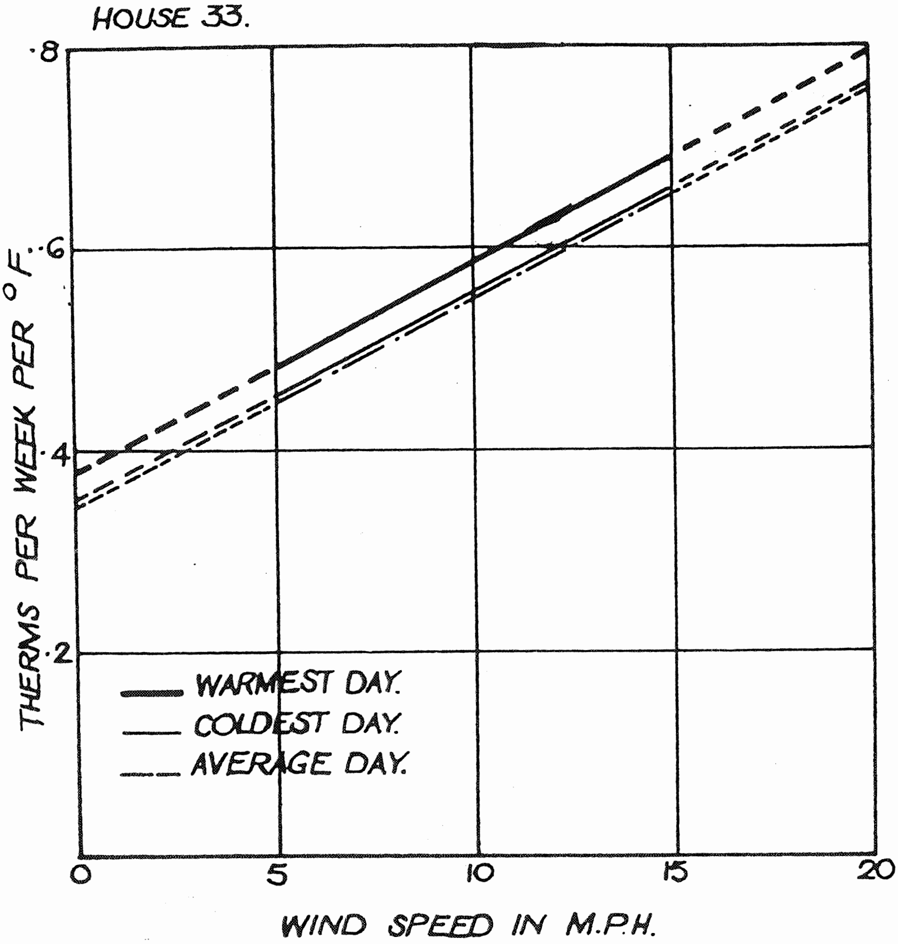


Fig. 9.—The Heat Loss Rate Prediction Equations for a House Calculated for Extreme and Mean Observed Temperature Differences.

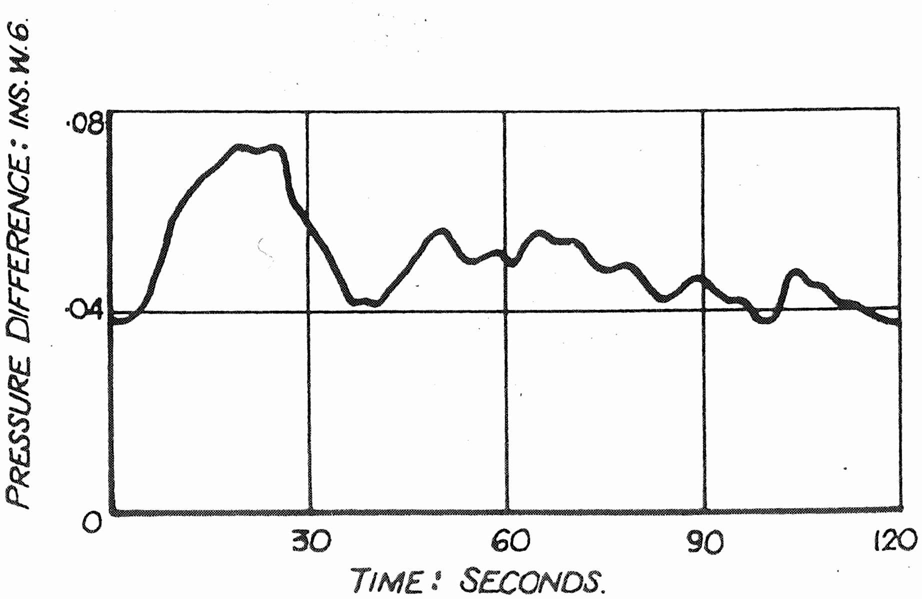


Fig. 10.—A Typical Pressure Record.

by a recording differential manometer which had a range of ± 0.1 in. water gauge. A typical record of the pressures measured is shown in Fig. 10. The effects of local gustiness near the house or the anemometer were minimised by recording pressures and wind runs over periods of 5 or 10 minutes, and then using the mean values in the subsequent analysis.

4.2. Results.

4.2.1. *Introductory.*

No significant difference was found between the pressures measured at different points on the same wall (any difference which existed being obscured by the variance of the results), and in analysis no differentiation has been made between such points. The pressure differences measured between the house and roof space were always found to be less than 0.004 in. w.g. and thus were smaller than could be accurately measured with the manometer available. Thus the measurements obtained resolve into the pressure differences between three external surfaces and the pressures acting across the three exposed walls.

In the presentation of results the pressure differences are denoted by P_{rs}, where the suffixes r, s indicate the points between which the pressure acts—w being used for the external surface of the west wall (front of house), e for the external surface of east wall, n for north wall and i for the internal measurement ; P_{rs} is positive when the pressure at r is greater than that at s, and thus for example, P_{we} is the pressure acting across the house from front to back. Where convenient the measured pressures (P_{rs}) have been expressed as fractions (K_{rs}) of the velocity head corresponding to the wind speed : at N.T.P. the velocity head is given by $0.00051\ v^2$ in. w.g. where v is in m.p.h. The mean direction of the wind is again specified by the angle θ which is made with the normal to the front of the house, θ being measured from the normal round the exposed side of the house : the predominant wind is approximately south-west, which for house 19 corresponds to $\theta = 340^\circ$.

4.2.2. *Pressure Differences Measured across the House.*

The measured values of K_{we} are plotted in Fig. 11 against the corresponding mean directions of the wind ; the results used are those in which the wind speed is greater than 5 m.p.h. It will be seen that there is no significant difference between the results obtained with westerly and easterly winds ($\theta = 0^\circ$, $\theta = 180^\circ$). The results indicate that the pressure curve does not have a pronounced peak, but it is difficult (with the distribution of observed directions around $\theta = 0^\circ$ and the variance in the measured K's) to say whether this portion of the curve is centred on $\theta = 0^\circ$ or displaced. Assuming that the peak does in fact occur at $\theta = 0^\circ$ and that K_{we} varies as $\cos^2\theta$ (so that the flow in a simple circuit from front to back of the house would vary as $\cos\theta$) the curve of best fit has been calculated and this is shown for comparison with the observed points. The equation found was :

$$K_{we} = 0.94 \cos^2\theta$$

$$\text{i.e. } P_{we} = 0.00048\ v^2 \cos^2\theta \text{ in. w.g.}$$

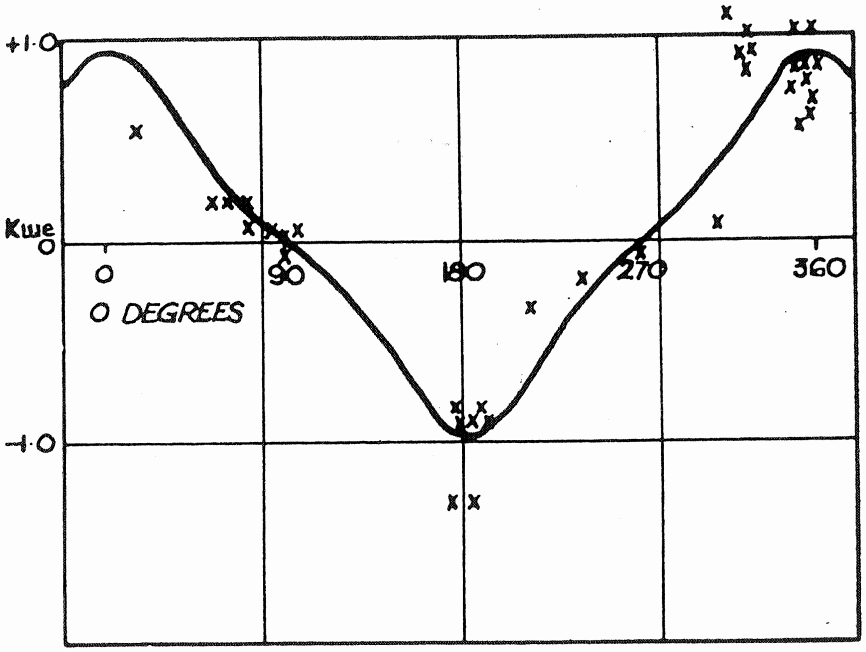


Fig. 11.—Variation of K_{we} with Wind Direction.

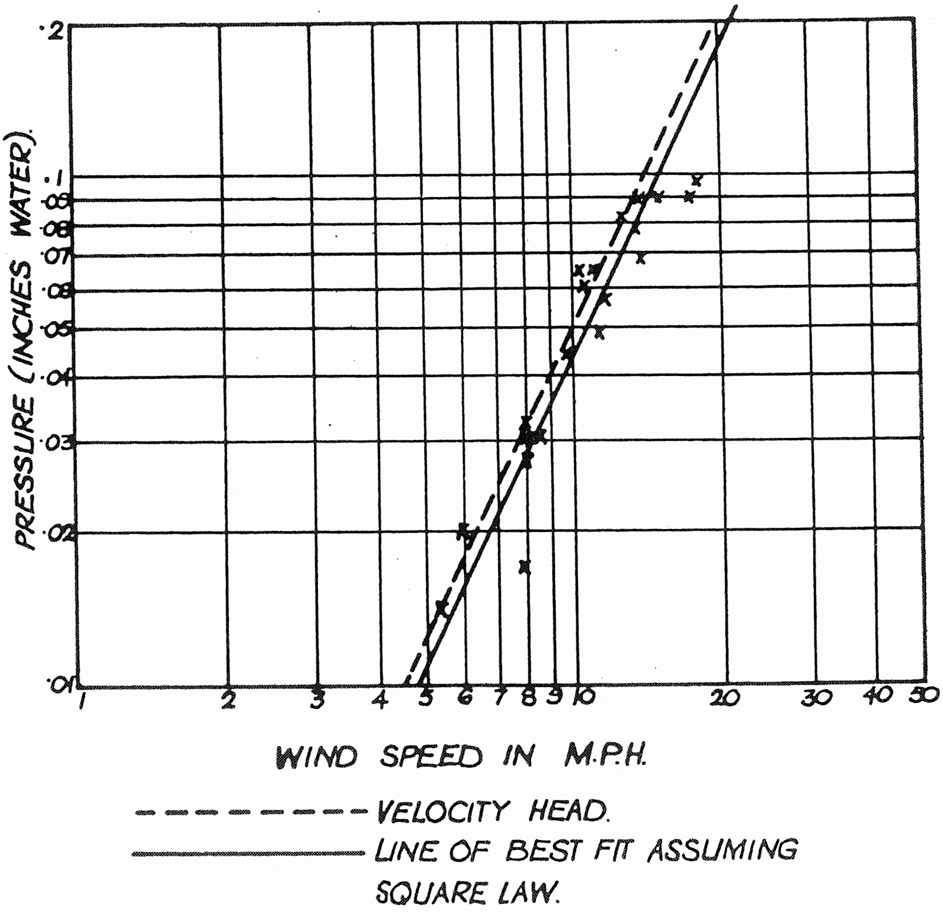


Fig. 12.—Wind Pressure across House when Wind is Approximately Normal to Front or Back of House.

where K and P have the sign of cos θ and v is in m.p.h. The standard error of the coefficient in the prediction equation for K_{we} was 0.06.

To show the measured variation of pressure with wind speed, the observed values with winds approximately normal to either the east

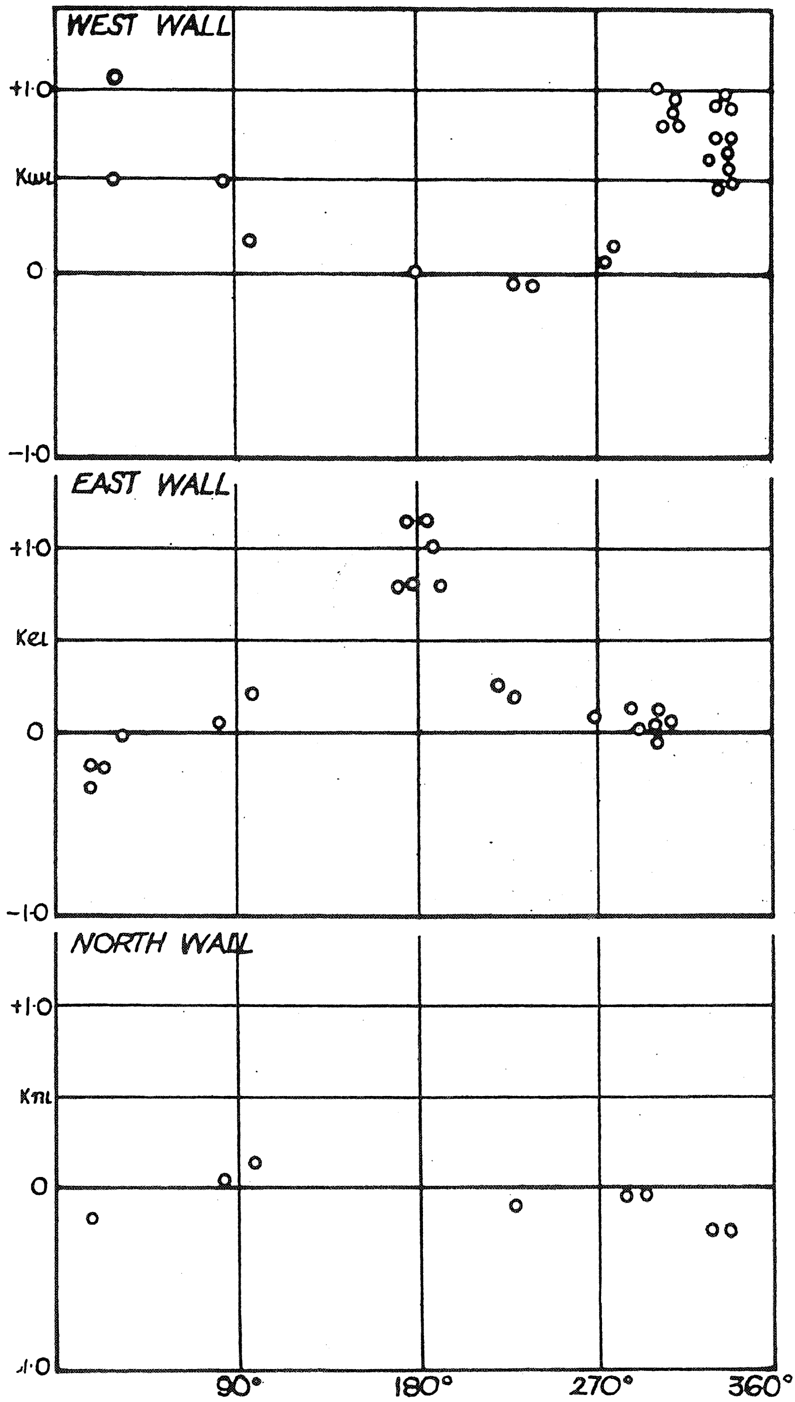


Fig. 13.—Variation of K_{rs} for the Three Walls with Wind Direction.

or west walls (i.e. in the regions of the peaks) have been plotted on logarithmic scales in Fig. 12. In this figure the dotted line represents the pressure corresponding to the velocity head, and the full line the line of best fit assuming that the pressure varies as the square of the wind speed : analysis showed that this assumption was consistent with the observed variation. The equation found was :

$$P_{we} \text{ (normal)} = 0.00044\, v^2 \text{ in. w.g.}$$
$$\text{i.e. } K_{we} \text{ (normal)} = 0.86, \text{ with a standard error of } 0.06.$$

4.2.3. *Pressure Differences Measured across the Walls.*

The observed values of K for the pressure differences across the three walls (when the wind speed was greater than 5 m.p.h.) are plotted against θ in Fig. 13. It will be seen that the largest pressure drops were measured across the east and west walls, and these when the wind was directed on the respective walls ; the magnitude of

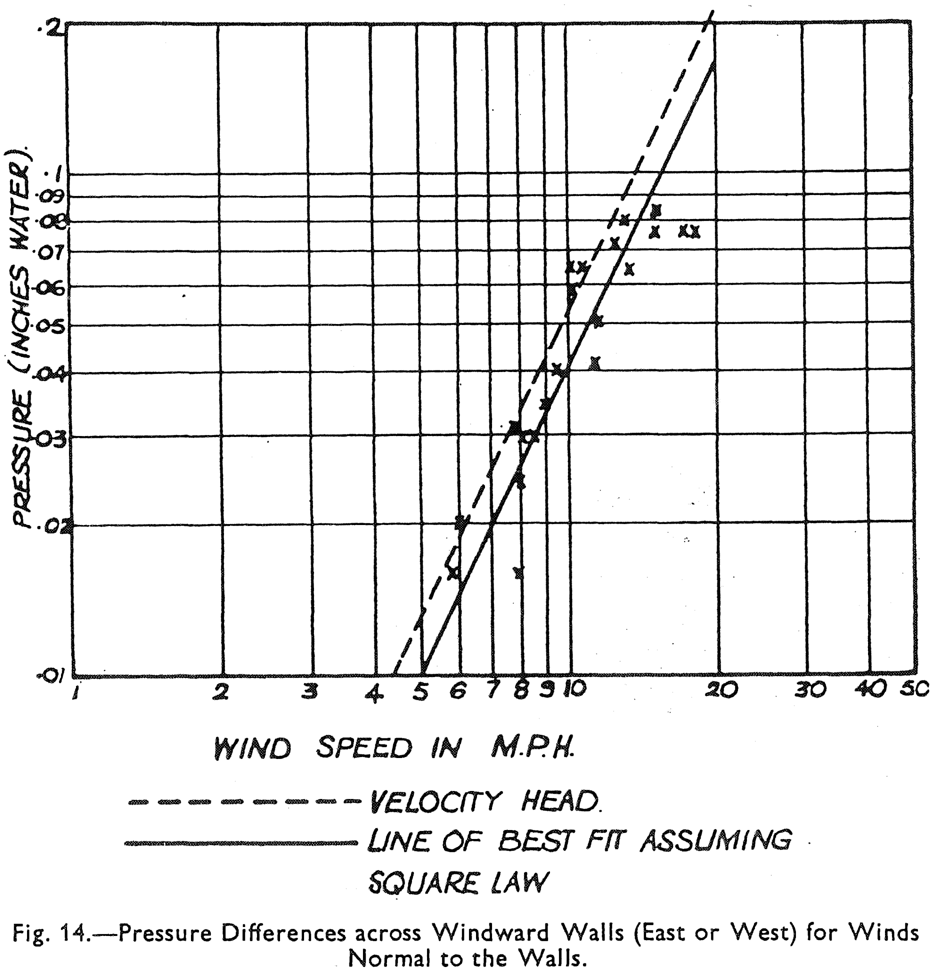


Fig. 14.—Pressure Differences across Windward Walls (East or West) for Winds Normal to the Walls.

these pressure differences does not differ greatly between the two walls. The pressure measured with winds approximately normal to the walls (the same ranges of θ as those used in plotting pressures across the house in Fig. 12) are plotted against wind speed in Fig. 14. The line of best fit assuming a square-law variation with wind speed is shown, in this case calculated to be

$$P = 0.00041\, v^2 \text{ in. w.g.}$$
$$\text{i.e. } K = 0.81.$$

Thus for normal winds practically all the pressure drop across the house (calculated in para. 4.2.2. as $0.00044\, v^2$ in. w.g.) occurs across the windward wall. This unequal division of the pressure drop is due to the magnitudes of the effective resistances in the air circuit when the wind is normal to an exposed face of the house. Air enters through apertures in the windward wall and leaves either through apertures in the other two walls or the ventilation ducts to the roof space. The resistance through which the air enters is thus much higher than the effective resistance in the remainder of the circuit (where the three resistances are in parallel). Take for example the case where air enters through a resistance R at a volume rate x and leaves through 3 equal resistances R which are in parallel. The pressure drop across the resistance in the entry is then Rx^2 whereas the pressure drop across the resistances in the exits (which in this case each carry $\frac{1}{3}x$) will be $R\ (\frac{1}{3}x)^2$ i.e., the total pressure drop will be divided in the ratio 9 : 1. An effect of this type will occur in a building if the air enters through one side of the building and leaves through more than one, and will be accentuated by the presence of flues which introduce low resistances in the outlet circuit. It is because of this effect that the air-change rate of a room has been found to be greater when it is on the windward side of the house.

4.3. Comparison with Model Experiments.

A considerable number of model experiments have been made by various investigators to determine the wind pressures on buildings and hence the coefficients to be used in computing the wind loading on structures. In particular, there are two comprehensive series of such experiments which have been made in recent years—in Denmark by Irminger and Nøkkentved[6, 7] and in England by Bailey and Vincent[8]. The papers reporting the results of these researches contain a wealth of data on the subject, including the effect of screening by adjacent buildings; the Danish papers also contain bibliographies on the subject.

Bailey and Vincent found that the variation of K_{we} for winds normal to one of the surfaces of their models could be attributed mainly to changes in the overall height of the models. They did not investigate the variation of K_{we} (normal) with the length of the building (all but one of the models had lengths equivalent to 100 ft.), but Irminger and Nøkkentved found a small variation of K_{we} (normal) with length of the building, and comparison with the variation with height shows the latter to be the dominant factor. From Bailey and Vincent's data the appropriate average value of K_{we} (normal) for the houses at Abbots Langley (overall height 26.5 ft.) is about 0.8. Irminger and Nøkkentved[7] found an average value of about 1.0 for a long line of houses with height equal to the breadth (to which the experimental houses approximate). Thus the observed value of K_{we} (normal) = 0.86 is in reasonable agreement with the model results quoted: the comparison can only be made in broad terms as no model exactly equivalent to the experimental houses has been tested, and also as the points on the surfaces where the full-scale measurements were taken do not give the average pressure on the surface. In a comparison of model and full-scale results in which absolute pressures were measured Bailey[9] found that in the full-scale tests the increase of pressure on the windward side was less (about 26 per cent. reduction) and the decrease in pressure on the leeward slope more (by about 50 per cent.) than in the model experiments ; the value of K_{we} (normal) which he found from measurements at the midsection of the walls were in closer agreement, being 0.94 for the full-scale trials and 1.14 for the model tests, an order of agreement similar to that shown above.

The variation in K_{we} as the angle of incidence of the wind changes has also been investigated in model experiments. Irminger and Nøkkentved[6] using a model with length, breadth and height ratios of 2 : 1 : 1 found that as the wind departed from the normal, K_{we} remained fairly constant until θ was about 40°, and thereafter the pressure dropped more sharply to its zero value when θ became 90°. These are features which are indicated in the present investigation, though it should be remembered that the model experiments were concerned with a single house and not a line of houses.

On the whole, however, it does appear that it should be possible to use the results of pressure surveys in model experiments to predict the air flow through buildings due to wind pressures, and for this there exists a considerable amount of information on the pressure on the walls and roofs of many types of buildings. It should be noted that as the square root of the pressure is used when calculating rates of air flow the effect of errors in the assumed K's will be reduced.

4.4. Calibration of Windows.

By combining the results of the pressure measurements with direct measurements of the house air-change rate (as described in the Appendix) an in situ calibration of the windows may be effected. When a wind of 8.5 m.p.h. is normal to the front of house 19 the estimated rate of air change with internal doors open is 1.8 per hour, which is equivalent to a volume rate of flow of 12,600 c.f.h. Laboratory tests on the ventilator (normally installed beside the front door) showed that with the pressure which is across it in the house with the above wind (taken as 0.81 times the velocity head) the rate of air flow was about 4,500 c.f.h. The flow through the weather-stripped door may be estimated at about 1,000 c.f.h.[10] so that the remaining 7,000 c.f.h. must enter through the windward windows. The crack length on the face is 74 ft. so that the rate of flow for the windows is estimated to be 94 c.f.h. per foot crack at the pressure observed when the wind speed is 8.5 m.p.h. Some figures of results obtained in American researches are available[10], and of these only one gives a larger value for infiltration (when the figures are reduced to the pressure assumed above), viz., industrial pivoted rolled section steel sash windows with a $\frac{1}{16}$th in. crack for which the comparable rate of air flow is 103 c.f.h. per foot crack. It should be remembered that the air-change rates measured in the rooms of house 19 during the heating trials were found to be significantly lower than in the prototype, house 13, and that this was subsequently traced to the fit of the windows. Thus the comparison with the American figures is even more unfavourable than indicated above. Inspection of the windows showed that although the high rate of flow was partly due to warping of unseasoned wood, it was also caused by faulty positioning of the hinges ; in many cases there were conspicuous gaps on the hinged side of the window. The accurate positioning of window hinges is an old difficulty, which might be met by marking the position of the screw holes during manufacture or alternatively one possible solution would be to use a slotted hinge so that fine adjustments could be made after installation if required.

5. DISCUSSION.

5.1. The Effect of Modifications to the Ventilation Systems.

The ventilation systems installed in the houses are unorthodox, and it is extremely difficult to estimate what the air-change rates in the rooms would have been with more normal types of ventilation systems. It is, however, possible to estimate (from the results of the air change and pressure measurements in house 19) the effect of changes of components in the external walls on the air-change rate in a house with internal doors open : the order of the effect of closing the internal doors can be obtained from the results in house 19 where the mean rate of air change was reduced from 1.8 to 1.3 per hour. The effect of these changes will be estimated for the mean wind speed of 8.5 m.p.h.

As a first modification, consider the effect of closing the inlet grille beside the front door in house 19 on the air-change rate when the wind is blowing normal to the front of the house. Closing the grille will increase the resistance in the inlet circuit and thus the fraction of the pressure drop across the house which appears across the windward wall will increase. This pressure however cannot increase by much, as even with the grille open about 94 per cent. of the pressure drop across the house occurs across the wall. Thus the rate at which air enters through the cracks around the windows and doors will not be appreciably affected, and will remain at about 8,000 c.f.h. (see para. 4.4.) which is equivalent to about 1.1 air changes per hour. When the wind is on the back of the house, closing the grille will have very little effect on the air-change rate in the house, as in this case the grille is normally in parallel with the low outlet resistance. At present the grille does compensate to some extent for the unequal lengths of window crackage at the front and back of the house (74 ft. as against 92 ft.) ; without it the air-change rates would be appreciably greater for winds on the back of the house than for winds on the front.

It has been shown how unfavourably the fit of the windows compares with typical American standards. Weatherstripping the windows could be expected to reduce the rate of infiltration from 94 c.f.h. to about 22 c.f.h. per foot crack for the same pressure drop across the windows[10]. Thus the rate at which air would enter when the wind is on the front of the house would be 7,100 c.f.h. with the front-door grille open and 2,600 c.f.h. with the grille closed.

5.2. Comparison with Other Results.

The air-change rates in rooms have been measured fairly extensively in recent years by a number of investigators notably Masterman[11], Warner[12], Bedford, Warner and Chrenko[13], and Carne[14]. In general the results obtained in these experiments were lower than the rates measured in the experimental houses, but apart from the effects of the unorthodoxy of the ventilation systems in the experimental houses there are other reasons why it is difficult to compare the results. The present measurements have been taken in houses on an exposed site ; the measurements referred to above were mostly taken in built-up areas where wind pressures will be less and stack effect will play a more important part in the ventilation processes—for instance, in Warner's series of experiments the average wind speed measured at working level was less than 2.5 m.p.h. Also there is very little information at present on typical cracks around windows in buildings.

5.3. Comparison with Standards of Ventilation.

The present minimum standards of ventilation in dwelling houses are based on Yaglou's experiments on the air supply necessary to prevent undue concentrations of body odour[15]. A comparison of the mean air-change rates measured in the rooms of four of the houses has already been made in Table II ; it will be seen that the actual rates are appreciably higher than the standards. It should be noted that all the air entering the individual spaces and producing air change therein is not necessarily fresh—for instance, with the wind on the front of house 13, air (which may or may not be contaminated) flows from the front bedroom into the hall and thence to the two back bedrooms. For a typical family of four, however, this interaction will not be an important factor as the concentration of body odour carried from one inhabited room to another will be small.

The prediction equations for the rates of air flow into and from the houses have shown how these are dependent on wind speed, and here is one of the basic problems of design when natural ventilation is adopted—if we design to have the required standard of ventilation at the mean wind speed, then the ventilation will be inadequate at lower wind speeds and unnecessarily high at high wind speeds. To obtain a more constant rate of air flow under such varying external conditions, the entry of air through cracks around windows and doors must be minimised (by weather-stripping if necessary) and provision made for either automatic or tenant control of the air flow into the house.

While discussing ventilation requirements, it is of interest to note that although the results of Yaglou's experiments in America have been adopted as a basis for our ventilation standards, the Americans themselves have not applied them to dwellings and have in fact no regulations in force which require the provision of air bricks for ventilation in flueless rooms. A possible explanation of why this is found satisfactory in America lies in the more open plan adopted there, which allows much more interchange of air between rooms. Now in the extreme case when perfect recirculation occurs between the rooms in a house, the requirements found by Yaglou would be satisfied for a family of four by a total air supply of less than 2,400 c.f.h. (the requirement per person diminishes as the space per person increases) as compared for instance with the requirement of about 8,000 c.f.h. calculated for adequate ventilation in the separate rooms of the experimental houses. Under the present by-laws flueless rooms in dwellings must be ventilated either directly to outside or to a lobby or corridor ; in most applications the first alternative has usually been adopted, but if the above is the explanation of the difference in regulations in Britain and America, then there would be considerable advantage (as regards reducing the rate of heat loss) by using the second alternative and encouraging recirculation with, say, a central hall.

6. SUMMARY AND GENERAL CONCLUSIONS.

(*a*) The average air-change rates in the closed rooms of the experimental houses were found to be appreciably greater than those required under present standards. A comparison with American practice suggests that adequate ventilation might be achieved with less loss of heat by encouraging recirculation within a dwelling.

(*b*) It was found that the air-change rates in rooms could generally be expressed by a linear correlation with wind speed, though in some cases the direction of the wind was also a significant factor. No relationship between air-change rate and stack effect or humidity was detected ; it is thought that the former will become more important in built-up areas where wind pressures are lower.

(*c*) The total rate of air flow into the houses was found to depend mainly on wind speed with the direction of the wind again a secondary factor. The average rate of air flow during the experimental period was found to be equivalent to about 2.0 air changes in a house per hour.

(*d*) The rate of heat loss from the houses by ventilation also showed a similar effect of wind speed and direction. The average rate of heat loss throughout the season was about 8 therms per week.

(*e*) A series of pressure measurements was made around a house. The results of this investigation agreed fairly well with those obtained in model experiments, and it is suggested that the latter could be used in the design of ventilation systems.

(*f*) An in situ calibration of the windows to determine the air flow through the cracks yielded figures which compared unfavourably with those obtained by measurements in America. Inspection revealed that this was due to warping of unseasoned wood and to inaccuracies in the positioning of the hinges, and it is suggested that the adoption of a slotted hinge be considered.

7. ACKNOWLEDGMENTS.

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APPENDIX

THE ESTIMATION OF AIR-CHANGE RATE AND TS COMPONENTS.

A.1. Air-Change Measurements in Rooms.

The air-change rate of a room is usually defined as the ratio of the rate at which air enters (or leaves) the room divided by the volume of the room. The effective air-change rates in different regions of a room need not necessarily be the same, but it is common to give an air-change rate for a room just as a room temperature is used when in fact there may be some variation in temperature throughout the room. The air-change rate is generally measured by introducing a tracer substance into the room, mixing it thoroughly with the air and then measuring the subsequent rate of decay. If there is complete mixing between the replacement air and the air in the room, the concentration of the tracer during the decay is given by:

$$-V\,dc/dt = xc$$

where c = concentration of tracer at time t.

x = volume of air entering (or leaving) the room in unit time.

V = volume of room.

and the solution for the initial condition $c = c_0$ at $t = 0$ is

$$c = c_0 e^{-\frac{x}{V}t} = c_0 e^{-yt} \tag{1}$$

where y = number of air changes in unit time.

Hence taking logarithms

$$\log_e c = \log_e c_0 - yt$$

so that by plotting the logarithms of the observed concentrations against time, the rate of air change is obtained from the slope of the best fitting line, and the rate of air flow from the equation.

In the experimental houses it was found that in the main body of a room there was little variation in the measured air-change rates so that the above could be applied. On the other hand the rates measured at different points in the space comprising hall and landing were significantly different; here the mean of the measured rates was used in subsequent calculations.

A.2. The Components of Air Change and Method of Measurement.

It will be seen that air-change rates, defined and measured as above, only yield the rates of flow into or out of a room and do not distinguish between exchange with the remainder of the building and exchange with the external air. The separation of air flow into these components is necessary both when assessing the adequacy of ventilation in a room (the air coming from adjacent rooms may or may not be contaminated) and also when estimating the heat lost by ventilation from a room or a building.

If during the decay of the tracer gas in a room, leakage occurs to an adjacent room through a ventilator or cracks around a closed internal door, the rate of air flow may be assessed from the concentration of the tracer gas in the second room. It was found that in the experimental houses this type of flow was generally unidirectional, that is, there was seldom reversal of flow, for instance, at the top and bottom of a door (the effect of temperature difference between the rooms was swamped by the effects of wind, heated flues and differences between internal and external temperatures). With a unidirectional flow from room 1 into an adjacent room (room 2) at a volume rate of x_{12}, the equations for the concentrations of tracer gas are :

$$-V_1\, dc_1/dt = (x_{10} + x_{12})\, c_1$$
$$-V_2\, dc_2/dt = x_{20}c_2 - x_{12}c_1$$

where V_1, V_2 = volumes of rooms 1 and 2.
c_1, c_2 = concentrations in rooms 1 and 2.
x_{10} = rate of air flow from room 1 to outside.
x_{20} = rate of air flow from room 2 to outside.

The solutions with the initial conditions $c_1 = c_0$, $c_2 = 0$ at $t = 0$ (obtained by sealing apertures between the rooms while the tracer gas is mixed in the first room) are :

$$c_1 = c_0 e^{-\frac{x_{10}+x_{12}}{V_1}t}$$

$$c_2 = c_0 \frac{x_{12}}{V_2} \frac{1}{\frac{x_{20}}{V_2} - \frac{x_{10}+x_{12}}{V_1}} \left[e^{-\frac{x_{10}+x_{12}}{V_1}t} - e^{-\frac{x_{20}}{V_2}t} \right]$$

If y_1 and y_2 are the prevailing rates of air change in rooms 1 and 2, equal to $(x_{10} + x_{12})/V_1$ and x_{20}/V_2 respectively, these equations may be written :

$$c_1 = c_0 e^{-y_1 t} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

$$c_2 = c_0 \frac{x_{12}}{V_2} \frac{1}{y_2 - y_1} \left[e^{-y_1 t} - e^{-y_2 t} \right] \quad \ldots \quad (3)$$

Hence when y_1 and y_2 are known, the shape of the leakage curve (i.e. c_2) may be calculated from equation (3) and compared with the measured concentrations ; by plotting the concentrations on a logarithmic scale against time, the multiplying factor c_0x_{12}/V_2 and hence x_{12} may be found by superimposing the theoretical and observed curves. Alternatively the observed maximum value for

c_2 may be used to give the multiplying factor, for the maximum occurs when :

$$y_1 e^{-y_1 t} = y_2 e^{-y_2 t}$$

i.e.

$$t = \frac{\log_e y_1/y_2}{y_1 - y_2}$$

and hence from equation (3)

$$\frac{x_{12}}{V_2} = \frac{c_2(\max)}{c_0} \frac{y_2 - y_1}{\left(y_1/y_2\right)^{y_1/y_2 - y_1} - \left(y_1/y_2\right)^{y_2/y_2 - y_1}} \qquad (4)$$

As an example of the type of measurement described above, the leakage concentrations observed in a room (room 2) during an air-change measurement in an adjacent room (room 1) are shown in Fig. A1. In room 1 the intial concentration was 20 units and the measured rate of air change (y_1) was 2.0 per hour ; the rate of air change in room 2 (y_2) was estimated from a prediction equation to be 3.6 per hour. The theoretical curve for the function was

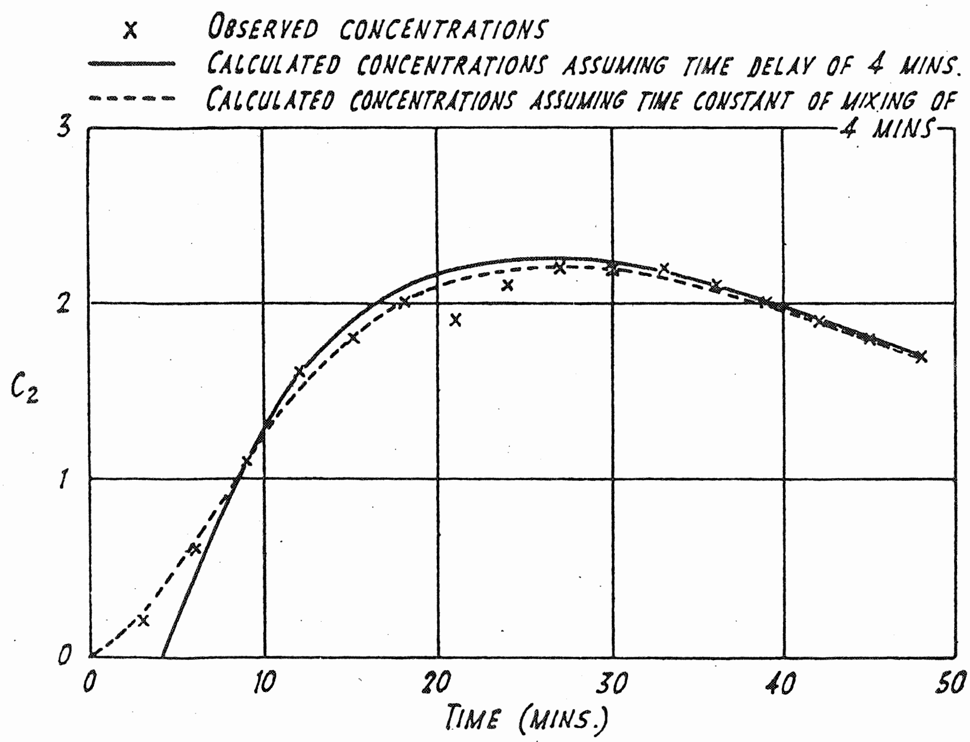

Fig. A1.—Example of Leakage of Tracer Gas to an Adjoining Room.

calculated by substituting these values of y_1 and y_2 in equation (3), and by plotting this function and the observed concentrations on a logarithmic scale and then superimposing as described above, the multiplying factor $c_0 x_{12}/V_2$ was estimated to be 17, and as $c_0 = 20$ hence $x_{12}/V_2 = 0.85$; to obtain a good fit between observed and calculated curves, a time delay of 4 minutes in the recorded concentrations had to be assumed. The calculated curve assuming that $c_0 x_{12}/V_2 = 17$, and that there is a delay of 4 minutes is shown as the full line in Fig. A1. It will be seen that agreement is good apart from the initial position of the curve, indicating that the time lag is due rather to a time constant of mixing in room 2 than to the time displacement which has been assumed in fitting the concentrations. The above process of calculating the theoretical curve and superimposing on the observed results has, therefore, been repeated on the assumption that there is a time constant of 4 minutes for the mixing process in room 2; the estimated value of $c_0 x_{12}/V_2$ was again found to be 17 and as will be seen from the dotted line in Fig. A1 the theoretical curve shows good agreement with the observed concentrations. It may be shown that a time constant due to mixing and recording, a process which is rapid compared with the rates of air change in the rooms, will only affect the initial shape of the measured concentration curve, but that the subsequent shape and maximum value will be virtually unaltered apart from a displacement in time. Hence it is valid when superimposing to neglect the initial measured concentrations and displace the curve in time if this is necessary to obtain a good fit.

In the present example, by substituting the observed maximum concentration in equation (4), the value of $c_0 x_{12}/V_2$ was again estimated to be 17. This method of comparing maxima being simpler was adopted for the calculation of the leakage flow in the present experiments.

A.3. Air-Change Measurements in Houses.

The air-change rate of a house can be determined by considering the outgoing air component from each room and summing throughout the house. The analysis is complicated and relies on satisfactory prediction equations being formed for the air-change rates and air flows in individual rooms. If interest is confined to the air-change rate of a house, it is preferable to make direct measurements which may then be examined with reference to the prevailing conditions. Such measurements may be made by introducing a tracer gas into a house so that the concentration is initially the same in all rooms of the house, and then measuring the simultaneous rates of decay in the individual rooms. If $y_1, y_2, y_3, \ldots$ are the initial decay rates in rooms, 1, 2, 3 ... with volumes V_1, V_2, V_3, then the rate at which air is leaving the house is given by :

$$y_1 V_1 + y_2 V_2 + y_3 V_3 + \ldots\ldots\ldots$$

and the air change rate of the house (volume V) is :

$$Y = \frac{1}{V}\left(y_1 V_1 + y_2 V_2 + y_3 V_3 + \ldots\ldots\right)$$

The rate of heat loss by ventilation may be directly measured by a similar technique in which the initial concentration in each room is made proportional to the difference between the room and external temperature.

DISCUSSION.

Dr. T. Bedford complimented the author on his excellent paper and his equally excellent introduction of it and demonstrations.

In regard to the very difficult question of the recirculation of air, he was inclined to agree with the author's remarks in Section 5.3

of the paper. If houses were built on the open plan, with perfect recirculation between rooms, so that the whole of the air within the house could be used as a reservoir, even if the people in the house were confined to one room the ventilation could be reduced to a considerable extent without difficulty. In the case of the family of four people, to which the author referred, he would like the total air supply to be more than 2,400 c.f.h., say, 4,000 c.f.h., but he could give no very satisfactory reason except that he felt that ventilation should not be reduced too much. He would like Dr. Williams to deal with that point.

He thought that there should be an upper and a lower aperture communicating with the central hall, so that the stack effect could be utilised, rather than a single aperture. He had in mind the L.C.C. Bye-laws, which required that any flueless room should have an opening of at least 50 sq. in. leading to the external air or an opening of at least 100 sq. in. leading to a corridor or lobby. He was very doubtful whether a single 10 in. × 10 in. hole over the door leading into the hall of the ordinary suburban house would provide a very good ventilation if the cracks round the windows were sealed.

Dr. R. E. O. Williams said that he was very grateful to the President and the Institution for giving him an opportunity to listen to Mr. Dick's address as well as to read the paper which had been circulated before the meeting. He would like to join with Dr. Bedford in congratulating Mr. Dick and the other members of the team working at Garston on the remarkable set of results obtained under field conditions. All those who had tried to do experimental investigations under the conditions of field work knew that the facts that emerged were very hard-earned indeed. He was sure that all the members would look forward to hearing of the results obtained from comparable investigations in occupied houses.

He would like to ask the author a few questions on the estimation of ventilation in dwellings. First, what sort of difference would tenant-habit make in the ventilation pattern, that was to say, would the agents which were clearly predominant in the uninhabited house, with windows and doors kept firmly closed, be the predominant agents affecting the ventilation rate in the inhabited house ; or would tenant-habits, in the way of opening windows and doors, have a predominating influence on the ventilation.

Could the author give any information about the actual technique of measuring the ventilation in the houses. He (Dr. Williams) was aware of the general system, but he wondered whether its complexity, in the length of pipe going round the whole room to liberate the tracer, was necessary, or whether it would be possible to use a simpler inlet and outlet system for the tracer gas. He asked this question because, in dealing with the effect of ventilation on health, it was necessary to measure the ventilation in a variety of places where some measure of health could be obtained.

Regarding the effect of air recirculation on health, he himself believed—this was a personal opinion and might not be accepted by everyone—that, in the ordinary occupation of a dwelling house by a family, the danger of spreading infection by the recirculation of air was not very great. In ordinary family life there were so many opportunities of conveying infection from one member of the family to another, other than by the air, that the risk of infection being conveyed by the circulation of air from the living room to the bedroom, for example, could not be serious. When, however, some room in the house was being used as a sick room, for a child with scarlet fever or an adult with tuberculosis for instance, the re-circulation of air from this room was undesirable. The possibility of houses being used as sick quarters temporarily must be borne in mind in building them ; they should not be built in such a way that it would be dangerous so to use them.

Dr. T. C. Angus said that at least one novel development in the art and science of ventilation was emphasised in this valuable paper, and that was the increasing use of statistical methods in the treatment of ventilation data. When a fan or an electric motor was tested by approved methods, a single satisfactory test was irrefutable and was all that could be asked for, but with houses, as with man and with the other living subjects of physiological research with important individual differences, it by no means followed that what was true for one specimen was true for others. So in work such as this a large number of controlled experiments were required and the results were best handled by statistical methods.

It was strange that there was not a greater difference between the air change in house No. 13 (central heating) and house No. 33 (open fire in the living-room). It had been shown that a single open fire extracts air at the rate of about 100 c.f.m., or 6,000 cu. ft. per hour. On this assumption and with the values for cubic contents given, the single open fire in House No. 33 would cause 2.95 air changes per hour in the living-room, and 0.86 air changes per hour in the whole house—a substantial contribution. The equality of air changes shown in Table III, and in Table IV (after weather-stripping) were surprising.

The air change in house No. 33 before weather-stripping was exactly 0.8 of an air change greater than that in house No. 13 ; as if the weather-stripping had neutralised the extra ventilation of the open fire—but that must be one of the too-exact coincidences which sometimes were found in experimentation. Otherwise it appeared to him that weather-stripping had less effect than one would anticipate. It might be that the majority of leaks were between the window and door frames and the walls rather than through the closed windows and doors themselves, as the poor quality of the timber suggested. Very considerable leaks of that kind were found in the experimental rooms at the Barnet Field Research Unit ; as he was able to show at the meeting a month ago.

He would ask the author if when calculating the heat losses in Table VI the rate of air change in each separate room and passage was calculated and its individual air temperature considered, or whether the air-change rate for the whole house was taken at a mean temperature. In the latter case the open-fire house, with cool passages, would show at a disadvantage.

At the beginning of the discussion Mr. Dick stated that in view of the unorthodoxy of the ventilation systems it would be difficult to determine what the ventilation rates of the houses would be if the ventilators were not there. It might be worth while to determine that by controlled experiments in which some houses could be tested with the ventilators and ducts open whilst in similar houses the air changes could be measured with the apertures sealed. Their experiments led to the belief that in view of the porosity of modern constructions the effects of small ducts were likely to have less effect than they might be inclined to think. He would close by adding his sincere congratulations to those of the previous speakers to Mr. Dick for his paper.

Mr. D. R. Wills said that he also would like to congratulate the author. He and his colleagues at Watson House found the results of the author's experiments most valuable and they admired the fundamental qualities of the work. The ventilation of houses was very important and unless the fundamental laws which controlled the ventilation were appreciated it was not possible to make any progress in designing ventilation systems.

In discussing the question of correlation, the author drew attention to the directional terms and rather anticipated the question that he wished to ask. The problem dealt with at Watson House mainly concerned built-up areas, and he would like to know what sort of modifications were necessary in the prediction equations, other than a simple velocity correction, in order to make them applicable to houses in more sheltered and built-up conditions. He thought directional terms, in certain cases, could be of importance, depending on the degree of sheltering.

He felt that perhaps too much attention was given to the question of general house ventilation as opposed to the ventilation of individual rooms. He would refer in particular to the kitchen and the bathroom, which might be regarded as the workshops of the house. The modern tendency was to make kitchens and bathrooms smaller and smaller. There was also another type of room which was coming into being, namely, the utility bathroom. He thought that in these rooms, despite the fact that the windows could be opened, a minimum degree of ventilation was necessary, and any research that could be directed towards the provision of efficient kitchen, bathroom and utility bathroom ventilation systems would be of great importance in increasing the general comfort of the occupants, the most important of whom was the housewife.

He had been intrigued by the experiment on the effect of areas in series and parallel. The question of open windows came into the subject of kitchen ventilation. It appeared from the general laws discussed by the author that if the kitchen was on the leeward side of the house and if the bedroom windows and other windows were open on this side, the opening of the kitchen window would apparently have very little effect on the general kitchen ventilation. Much however would depend on other relevant factors such as layout of rooms, position of main inlets, etc.

On the question of buildings in built-up areas, he would like to refer to a type of building to which the author's results could not very well be applied, namely, flats. In the case of flats it seemed a much more complicated problem to get air into or from the rooms which one wanted to ventilate, and he wondered whether there would be an extension of the author's work to cover flats.

The other question in whch he and his colleagues at Watson House were particularly interested, apart from the ventilation of buildings, was the question of pressure on the leeward and windward sides of houses and flats. They were concerned with the development of appliances working on balanced flue principles. Could the author give any idea of the maximum gust velocities reached during the tests and also their duration ? He would also like to know whether there were any periods of complete calm, particularly in built-up areas.

In taking pressure measurements, had any attempt been made to take them in a plane normal to the wall ? He would like to know that because he was interested in the way in which the pressure varied some small distance away from the wall.

In regard to the use of prediction equations for the estimation of fuel consumption, he would like to know whether any direct comparison had yet been made with the degree-day method, which had been in use for some years with more or less success. He wondered whether, if the heat losses were assessed correctly, i.e. if the average wind velocity was chosen correctly, there was a fairly close approximation between the degree-day method and the use of the prediction equations.

In regard to the air-change measurements, the author mentioned that the use of the term "mean air change" or "average rate of air change" could be likened to the use of the term "average temperature measurement." He wondered whether that was so. In heating systems, temperature gradients occurred from floor to ceiling, and he wondered whether, in some of the houses with different ventilation systems, the average figure was obtained from weighted samples taken at different levels which might have shown an appreciable air-change gradient from floor to ceiling. The aim should be, he assumed, to get ventilation or a reasonable rate of air change at breathing level or somewhere near it, and if the air change of 3 or 4 was based on a very small air change at ceiling level and a very large one at floor level, which could occur (it certainly did in his own house), the average rate of air change could be a figure which could be misleading in some respects.

He and his colleagues were particularly interested in the method of estimation of air change described in the paper. They had always used carbon dioxide as the tracer gas and analysed the samples on apparatus such as the Haldane, and he would like to know what was the degree of repeatability of the results when the author's method was used, with hydrogen or helium as the tracer gas. Had any experiments been done in which it had been possible to control the ventilation rate accurately and to repeat the results ?

Although the author mentioned the average standard deviation of results compared with the prediction equations, he would like to ask whether the accuracy of estimation varied at all with the air-change rate. He had sketched some of the curves and found that, if there was an air-change rate of ½, the rate of decay in 20 minutes was from 0.3 to 0.253 ; with 2 air changes, it was from 0.3 to

0.154 and with 4 air changes it was from 0.3 to 0.079. He could well imagine that the accuracy would have to be high to enable one to get the same degree of accuracy with a high air-change rate as with a low air-change rate or vice versa.

In conclusion, he would like to express his sincere appreciation and that of his colleagues at Watson House of the co-operation, helpfulness, and patience which the author and his colleagues had always shown to them when they visited the Building Research Station.

Mr. J. S. Hales said that he would like to congratulate the author on his excellent paper and on the valuable amplification of the paper which he had given in his introduction. The subject with which the paper dealt was an extremely difficult one, and a very large number of factors contributed to the ventilation. The author had shown the effect of some of these variations, and these had been further amplified by the figures shown.

There appeared to be two different types of dwellings, namely, the "exposed" dwelling, which seemed to be characteristic of the houses referred to in the paper, and the "sheltered" dwelling such as in a built-up area. There was a considerable difference between them, and it appeared to him that the sheltered type of dwelling predominated in this country.

Most people considered that the ventilation rate in the case of sheltered buildings or rooms was controlled very much more by the heating appliances used than by the wind or the atmospheric variations, and he thought this was borne out by some of the figures which the author had given.

He and his colleagues had always been interested in the ventilation rate as shown by the rate of flow in the chimney, and he had been very pleased to see some of the figures which the author had given in his tables, showing the relative areas of doors and windows which had to be dealt with. This had a distinct bearing on the type of appliance which was installed, and the author had rightly pointed out that the type and size of throat which was employed might have a considerable or even over-riding effect on the ventilation in a particular room, especially in the case of the sheltered type of room as distinct from the exposed room.

Typical figures obtained in the average sheltered house might be of interest to the meeting, because they linked up somewhat with the figures for equivalent area given in the author's tables. Measurements in existing rooms and experimental rooms had shown for example, that in the case of a sheltered room, with air speeds below about 5 m.p.h., having an ordinary open fire with about 50 sq. in. of throat area, a flow of about 6,000 c.f.h. was obtained in the flue. The throat area had to be reduced to about 20 sq. in. before the volume flow was reduced to 4,000 c.f.h. In the case of certain special fireplaces the area at the throat could be reduced to 10 sq. in. and the volume flow was then brought down to 2,500 c.f.h.; the area had to come down to 5 sq. in. before the volume flow could be brought down to 1,500 c.f.h. That indicated that, if any appreciable change was to be made, it might be necessary, as the author had indicated, to bring the effective areas down to below 10 sq. in.

before one started seriously to reduce the overall volume flow. He would like to hear the author's observations on the figures which he had given.

In connection with the centrally-heated house the air changes were given in relation to the wind speed, and he would like to know whether the author attached any special significance to the extrapolation back to zero wind speed, which seemed to indicate that in that particular instance there was in fact no stack effect, although there were, he believed, 50 sq. in. of ventilating duct in the living room and 30 sq. in. of ventilating duct in the bedrooms. It seemed to him that under those conditions there would be an appreciable air change, although the extrapolation suggested zero air change.

Dr. T. C. Angus said he had that day received a letter from Professor Theodore Hatch who, having bought an old house near Pittsburg, was bringing the heating arrangements up to present-day American standards. He had found that the flues of open fireplaces in this house were extracting 12,000 cu. ft. of air per hour under the influence of the central heating with no fire in the grate.

Mr. D. G. Lewis, in congratulating the author on his paper, said that he thought all who read it would benefit from the fundamental information given, which would have helpful effects on design. The paper was of interest not only to members of the Institution but also to gas engineers and all others concerned with the subject of the paper.

The remarks made by the author about the recirculation of air to other rooms in the house and the comments on that item made by Dr. Bedford and Dr. Williams led him to think that it might be possible to obtain some sidelight upon it by considering any health figures which could be obtained from Sweden and France. In Sweden the houses, apart from the bathroom and the kitchen, were virtually one large room, with a number of movable partitions, so that the members of the family, wherever they might be in the house, obtained the benefit of the air change of the whole house. The same feature applied to some of the middle-class flats in France, particularly in Paris. He did not know whether the French had designed communicating doors for convenience or economy of floor space but it had occurred to him when he was sitting in a French flat where there were no passages, halls or lobbies, that they may have also considered ventilation. He had sat in such a flat with the doors to all the other rooms, except the kitchen and toilets, open, so that, although the windows were closed, he had obtained the benefit of the air volume of most of the flat. He did not know whether there were any health figures available in connection with that section of the population who lived in such flats, but if there were, they might be useful.

He believed that in the Institution's " Guide to Current Practice " the heat transmittance coefficients for the exposed surfaces were given in six columns according to the exposure factor, and were related to wind speed. Therefore, the author, having now related wind speed to ventilation rates could perhaps produce a table of air changes for various exposures in the lower floors and upper floors of tall buildings covering the same range of exposures given in heat transmittance table, and he thought these would be of great benefit to the members of the Institution.

Mr. S. G. Crawford said that he would like to apologise in advance, in case he made any too naive remarks, as he was not an expert on the subject of heating and ventilating, but there were certain very interesting points in the paper on which he thought the author might be able to give a little more information.

The first concerned the model experiment which the author had shown and which was such a remarkably vivid demonstration of the point that he wanted to make. Could the author say to what extent the ventilation rates on the model could be scaled up to full size? He realised that it was possible to deal with pressures on the model scale, but the actual flow rates which were determined by the orifices put in the model might influence the situation in a way which would make it difficult to scale them up to full size.

After reading the paper and seeing the equations which the author had put on the board, he must confess that he was still a little puzzled about the equation in which V was proportional to the square root of the pressure head. He would like to know on what basis that equation rested.

The author had demonstrated in his paper, as a result of experiments, that the ventilation rate was proportional to the wind speed, and the degree of reliability, of course, could be assessed by the scatter of the points on the straight line which the author had drawn. Was the question of the flow being proportional to the square root of the pressure head connected in any way with whether the flow happened to be laminar flow or turbulent flow? For instance, in a pipe below the critical Reynolds number the quantity of air or liquid passed was proportional to the pressure difference, and, since the pressure difference was proportional to the square of the velocity, the quantity passed was proportional to the square of the velocity. When, however, the flow became turbulent, the quantity passed was proportional to the square root of the pressure difference and the quantity passed was proportional to the velocity, as the author had shown.

He had been doing some experiments on an isolated building, using the tracer technique in a rather different manner from that which appeared in the literature, and, although he was only able to get a rather small number of results, compared with the excellent series which the author had obtained, he had found very strong evidence for the ventilation rate being proportional to the square of the wind velocity above a wind speed of about 5 m.p.h. Round about the 5 m.p.h. mark, the different ventilation rates obtained on different occasions were extremely scattered, and, not knowing very much about the subject, he had imagined that the effect was probably due to other causes, comparable with that due to wind, namely, internal and external pressure differences and other things of that kind, due to the different temperatures caused by the fact that the sun was shining on the house or the inside of the house was heated in some way, and so on. He would be very grateful if the author could make some remarks upon that point, because it had been implicit in many of the comments made in the discussion that it would be possible to deduce ventilation rates for different wind speeds from the law mentioned by the author, yet there was this little divergence between the results to which he had just referred and the results which the author had obtained experimentally and quoted in his paper.

Some interesting remarks had been made in regard to houses in built-up areas. It was true that the wind speed in a built-up area was less than the wind speed well above the houses or in an adjacent very large open area, and the factor of one-third was approximately correct ; it varied, of course, according to the degree to which the area was built up. There was, however, another point to be considered in the case of a built-up area. In such an area there must be many vertical air movements, and he would like to know what effect those would have in controlling ventilation. They were not normally measured by the ordinary instruments used for measuring horizontal velocity.

In the few experiments which he had been able to carry out he had found, as the author had found in his experiments, that the effect of wind direction was very small. He was not quite sure why that was so, but when he took all the results that he had obtained from different points of the compass and plotted the ventilation rate against the wind speed he had not found any evidence that wind direction played an important role in the overall ventilation of the building.

Mr. M. S. Jones said that just before the war, physicists looking—perhaps from a distance—at the sphere of ventilation, had observed with some feeling of dismay that the whole subject appeared to be disappearing into large ducts. Post-war development, however, had shown that outside all the ducts, there still lay an interesting province of advance in natural ventilation, and Mr. Dick's paper was, he thought, one of the most important factual contributions recently made in this field. He personally had read it, not so much with surprise at its results, as with extreme interest and a feeling akin to excitement at the way in which the data had been co-ordinated. It was particularly welcome not only because of its factual content, but also because in several ways it illustrated that the laws of physics, which, as the atomic bomb had shown, worked very well in other directions, could also be very useful in the much more mundane and highly humane subject of ventilation.

In his simple example demonstrated on the blackboard, the author had favoured the quadratic law of connection between pressure drop ΔP and the rate of flow Q thereby induced through apertures. In certain circumstances, however, the effective index of the rate of flow involved proved to be somewhat less than 2. He felt that it might be helpful to put forward the suggestion that, instead of the customary power law

$$\Delta P = AQ^m,$$

with a curious empirical index m whose value varied considerably both with the rate of flow Q and with the nature of the aperture on account of variation in the Reynolds number, use might be made a binomial law of the form

$$\Delta P = AQ + BQ^2,$$

in which the pressure drop was proportional to a constant A times the rate of flow plus another constant B times the square of the rate of flow. Such a formulation admittedly did scant justice to the notable work of Osborne Reynolds, for it disregarded the existence of a critical velocity of transition between streamline and turbulent flow ; but it had the practical advantage that at both extremes, rate of flow tending to zero and rate of flow tending to infinity, it gave the correct forms corresponding respectively to laminar flow and to complete turbulence. He considered that it was capable of representing a quite large range of phenomena. The binomial formula also had the advantage that, instead of an index m itself dependent on the rate of flow, it possessed coefficients A and B which could remain sensibly independent of the rate of flow, the indices 1 and 2 of Q being invariable.

The other subject to which he wished to refer was the very interesting one of ventilation exchange between rooms. In a recent paper* emanating from the London School of Hygiene and Tropical Medicine, but not cited by the author in his bibliography, attention had been directed to the significance of a matrix of mutual ventilation coefficients between adjoining rooms. Mr. Dick's paper was a very encouraging one in this respect, because it showed in a concrete way, illustrated by experimental results, that such a scheme of coefficients was not unrealistically ambitious, but could be, and probably would have to be, increasingly applied to practical problems in the future. He looked forward with interest to the vast body of further experimental data which would probably flow from the B.R.S. experiments.

Mr. J. B. Dick, in replying to the discussion, referred to Dr. Bedford's remarks and said that he did not know whether the statutory opening of 100 sq. in. placed above the door would be sufficient for recirculation or not, but there was the possible alternative of using two grilles separated by a distance of 3 or 4 ft. so as to obtain a stack effect. This might not be necessary of course ; he thought that experimental data would show whether it was or not.

In regard to the effect of tenant-habit on the ventilation of a house, to which Dr. Williams had referred, it had been found that with tenants in occupation of an experimental house the wind speed still played an important part in the ventilation. The window-opening habits of the tenants also played an important part, and since these habits were related to the prevailing wind speed, the problem of the separation of the various effects was complicated. He hoped, however, to be able to give Dr. Williams some exact information on the point in the near future.

On the question raised by Dr. Williams whether a simpler installation could be generally adopted for measuring the ventilation in occupied houses, he had tried a simple system in which he liberated a certain amount of hydrogen or helium in one corner of a room,

*E. T. Renbourn, T. C. Angus, J. McK. Ellison, L. M. Croton and M. S. Jones, "The Measurement of Domestic Ventilation", *Journal of Hygiene*, March 1949, Vol. 47, pp. 1-38.

but he had not obtained a good distribution. He had had to use carburettor jets placed round the room in order to get a good distribution of the tracer.

Mr. Wills had raised the question of built-up areas. He and his colleagues did not know very much about the pressures in built-up areas, but they hoped to be able to deal with them some day. As a guess he would say that in general the wind velocity term and not its direction was the important term in the case of suburban dwellings, but of course there were individual rooms, as the experimental work had shown, where direction was important.

Mr. Wills had also asked about the periods of calm and windy weather. He was actively investigating this subject, but on a rather longer time scale than that in which he thought Mr. Wills was interested : he presumed that Mr. Wills, in mentioning gustiness, was thinking of balanced flues. He was examining what periods of calm weather occurred and this he thought would be of interest to Mr. Wills. On the gustiness question he thought that recourse would have to be had to the Meteorological Office.

The comparison between the use of the prediction equations and the use of the degree-day method, which was another point raised by Mr. Wills, had not yet been made but this was one of the results which would ultimately be obtained from the experiment.

Little variation of air-change rate had been found in the main body of the rooms of the houses. The external doors were of course weather-stripped, so that the entry of low-level cold air was prevented, and the air entering either came through a ventilator at about 4 or 5 ft., or, alternatively, came through the distributed inlet formed by the cracks around windows.

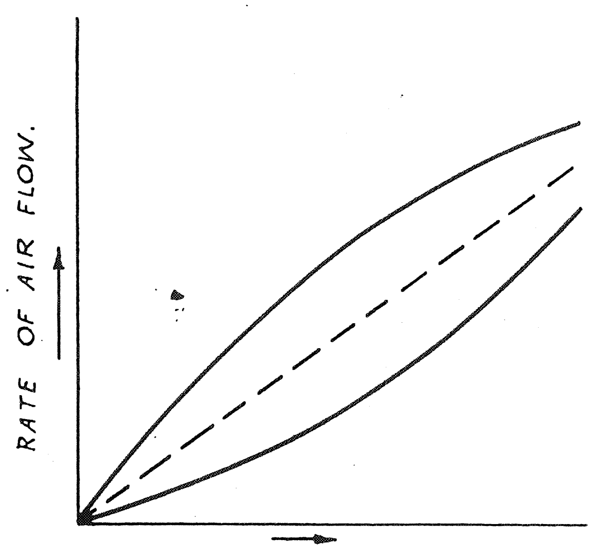

Fig. D1.

He agreed with Mr. Hales that it was dangerous to extrapolate back to get the air-change rate at zero wind speed. Some peculiar things happened in that region. He remembered doing a calculation on combined wind and stack effects in a building. Assuming the same number of windows upstairs and downstairs, front and back, in a house similar to one of the experimental houses, he had calculated the air-change rate for a temperature difference of 20° F. and winds of varying speed normal to the front of the house. He had assumed the fit of the windows to be such that there was one air change per hour at zero wind, and the type of curve that he had got for the air-change rate was as Fig. D1.

When the wind speed became high the stack effect played no part and the air-change rate was proportional to the wind speed, but stack effect became the predominant factor when the wind speed dropped below 3 or 4 m.p.h., i.e. when the pressure due to stack effect was greater than the velocity head of the wind. So apart from the usual hesitation to go beyond the measured range, in this case there was a definite danger in extrapolating back to zero wind speed.

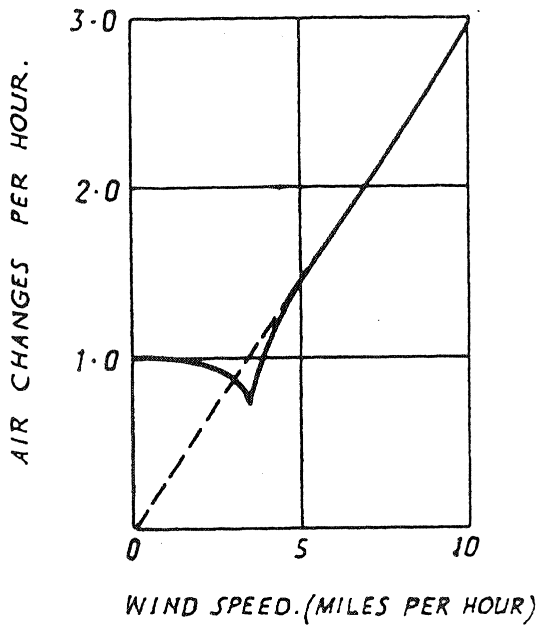

Fig. D2.

Both Mr. Crawford and Mr. Jones had raised the question of the index of the pressure term in the flow equation. He agreed with Mr. Jones that an empirical form of flow equation would be useful. He and his colleagues, when measuring in the Laboratory rates of air through windows, had found that the index of the pressure to which the flow was proportional could be greater or less than a half and that this was mainly due to actual movement of the windows. Plotting the air flow against the wind speed equivalent to the pressure across the window one could get curves following the forms shown in Fig. D2.

These forms were to be compared with the straight line when the index was a half. It had been found that some types of windows tended to open and others tended to close as the pressure across them increased, and so far no attempt had been made to separate these effects from those associated with laminar and turbulent flow.

Mr. R. Duncan Wallace, in proposing a vote of thanks to Mr. Dick, said he was sure that everyone present had appreciated Mr. Dick's paper and his address that evening and replies to the questions.

He hoped that later on it might be possible for Mr. Dick to carry out some experiments on industrial buildings to show rates of air change, as they would provide some very useful information.

The vote of thanks was accorded with applause, and the meeting then terminated.

Mr. J. B. Dick (communicated) : I was very interested to hear the comments by Dr. Bedford and Dr. Williams on the possibility of recirculation, and to learn from Mr. Lewis that it is in effect used in Sweden and France. I agree with Dr. Williams about the need for having a bedroom which can be isolated, but was glad to know that there were no other objections.

Dr. Angus was rather surprised at the small difference between the mean air-change rates in the living rooms with open fire and central heating. This is partly due to the mean wind speed used—if for instance the rates had been compared at 5 m.p.h. the difference would have been larger. There is also a possible variation in the two rooms in the fit of the windows or the cracks between the frames and surrounds, more probably in the former they were much the larger. In reply to the last query by Dr. Angus, the heat losses from the houses were calculated by summing the heat losses from individual rooms.

In reply to Mr. Wills' question about the effect of an open kitchen window when there is another window open on the leeward side of the house, the overall air flow through the window will certainly be reduced, but air change may well be obtained by rapid air movements into and out of the window. Regarding pressure measurements, we have not made any in a plane normal to the wall. The degree of repeatability of measurements is I think best given, so far as instrumental errors are concerned, by comparing the rates of air change indicated when the same sample is measured by a number of katharometers in turn. Such tests show that the accuracy which can be achieved is high, the standard deviation of the individual readings being of the order of 5 per cent. of the mean estimate. The time constant of our katharometers is about 15 seconds with hydrogen and this does not appreciably affect the measured air-change rates even up to 10 air changes per hour.

Mr. Hales' figures for the air flow in heated flues are very interesting. They demonstrate clearly the compensating increase in the aeromotive force in a flue when the throat is restricted to reduce the rate of air flow, and show that the throat must be considerably reduced before the air flow reaches a reasonable value.

In reply to Mr. Lewis it is not yet possible to give factors for the ventilation rates to be assumed according to the exposure, but we are certainly moving in that direction.

Mr. Crawford raised the question of the use of model experiments. The acting wind pressures can be reproduced in models and I think that the flow through cracks around windows could be reproduced without affecting the pressure pattern ; with open windows there might be some interaction. I agree with Mr. Crawford about the effect of wind direction on ventilation rate and think that this is due to the re-alignment of the orifices as inlets and outlets as the wind direction changes.

Mr. L. Gordon Davies (communicated) : I should like to congratulate Mr. Dick on the thoroughness of his work involved in the tests on the natural ventilation of houses, and on the very useful results which have been obtained. The information regarding window cracks is quite surprising and gives us new food for thought. Other facts, figures and formulæ given might well be used as standards, particularly as we can now calculate the rate at which air passes from a room to outside for any direction of wind and in terms of wind speed, and from which the ventilation heat loss can be found.

As the rate of air flow through the house depends mostly upon the wind pressure and that air-change rates are usually expressed as a linear correlation with wind speed, some form of automatic control limiting that flow to a predetermined velocity is essential, particularly if better fitting windows are provided or if some form of weather-stripping is fitted to the existing windows and outer doors. The constant flow ventilator for providing fresh air to the room or hall is admirably suited to this automatic control of volume and gives limited inward velocity irrespective of the outside wind pressures. Its performance represents very closely the chart which Mr. Dick showed at the lecture. The use of the constant flow ventilators in partition walls also would encourage circulation within the house which would cause the otherwise varying internal pressures to become more balanced.

It is, I think, still very debatable whether the condition of a room occupied, say, by four people for one hour or more and ventilated mostly by leaks providing the equivalent of two air changes per hour, could be considered healthy, as stuffiness leading to drowsiness and lassitude would soon be apparent. However, this is a point, as Dr. Angus has already said, which would have to be clarified by the medical profession.

Perhaps the phrase " air change per hour " is the wrong one to use as a standard for ventilation, since the velocity of air movement increases in direct proportion to the distance it moves for a given air change per hour. For instance, assuming perfect cross ventilation is possible in a room, say, 12 ft. square, then the speed of air movement across that room for one air change per hour would be 0.2 ft. per min., a movement much too low for healthy conditions. The air change per hour of cross ventilation in, say, a multi-storey factory 60 ft. wide would be equal to the speed of air movement of 1 ft. per min. Although in both cases the standard of ventilation of one air change per hour is the same, the speed of air movement in the factory is five times that of the house room. Furthermore, it is generally recognised that the number of air changes per hour required for a factory is considerably more than for a house. For example, if the air change of a house per hour is to be, say, one and the number of air changes per hour for a factory, say, three (for sedentary occupations) the rate of flow across the factory would in this case be 15 times faster than the flow of air across the smaller room, and yet most people spend more time in their home than they do at work.

While it is known that perfect cross ventilation cannot be provided or maintained and that the movement of room occupants and usage of doors increases the speed of air movement considerably above the 0.2 ft. per min. mentioned above, there is still a very big discrepancy between it and the 30 ft. per min. recommended by Bedford, and below 20 ft. per min. stuffiness is experienced. Bedford also records that 72 ft. per min. with a mean variation of 47 per cent. gives a pleasant and invigorating environment in a well-ventilated workroom, and that 15 ft. per min. with a 16 per cent. mean variation gives a poorly ventilated office.

Perhaps some basis other than air changes per hour can be devised which will enable calculation to be made to provide the best working and living conditions.

Mr. J. B. Dick (communicated) : I agree with Mr. Gordon Davies about the necessity for adequate air movement. While appreciating that this is partly caused by cross ventilation, I think that in closed rooms it is mainly caused by convection currents produced by the heating system itself or by temperature differences between the surfaces of walls and windows and the air in the room. Some data has been published on the part played by the heating system* and this shows the range of air movement which can be obtained with different appliance.

*A Study of the Ventilation of a Warmer Room, carried out at the Building Research Station. *J. Inst. Heat. Vent. Eng.* 1939, 7, 428-48.