JOURNAL SECTION

Measurement of Ventilation Using Tracer Gas Technique

by J. B. Dick*, Garston, Watford, Herts., England

SUMMARY — The ventilation measurements now being made at the Building Research Station, England, are outlined. The use of a tracer gas technique to measure the air change rates in rooms is described, and it is shown how this technique has been extended to the estimation of the rate at which heat is lost by ventilation processes from heated rooms and houses. A description is given of the installation in the experimental houses which enables these measurements to be made when the houses are occupied without interfering with the normal life of the tenants.

THE VENTILATION measurements taken in residences at the Building Research Station, England, are part of the general program of post-war research in heating and ventilation being conducted by the *Building Research Board* of the *Department of Scientific and Industrial Research.*[1]

The house heating tests are designed to give much needed data on the performance of heating systems and the value of insulation. In each of the tests made to date, there have been two distinct periods: (1) the unoccupied period in which the heating appliances were tended by laboratory staff members and the houses were heated to the required temperature levels with doors (internal and external) and windows closed and (2) the occupied period in which the tenants led their normal lives and thus controlled the temperature levels and the opening of doors and windows accordingly.

When considering the results of such tests from the point of view of both efficiency and economics, it was necessary to know the heat loss from the house by ventilation.[2,3] The natural ventilation systems were designed to suit the different heating systems in the houses and varied between houses. It was necessary, therefore, to determine air change rates in the rooms for both occupied and unoccupied periods. These requirements have been met by developing the methods for measurement of air change rate described in this paper and applying them as illustrated by examples of the measurements taken in the two periods.

The houses concerned in these trials were two story semi-detached buildings containing seven rooms with a total volume of about 7000 cu ft, and during the unoccupied period were heated to an average of about 20 F above the external temperature.

*Engineer, Building Research Board, Department of Scientific and Industrial Research, England.

[1]Exponent numerals refer to references.

Air Change Measurements Using a Tracer

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 are not necessarily the same, but it is common practice to refer to an air change rate for a room, just as a single room temperature is used to express room temperature when, in fact, there may be some variation in temperature throughout the room. In recent years, the air change rates in rooms of both apartments and houses have been measured by a number of investigators by introducing a tracer substance into the room, mixing it thoroughly with the air, and then measuring the subsequent rate of decay.[4-8] 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:

$$-v\frac{dc}{dt} = xc$$

where

c = concentration of tracer at time t.

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

v = volume of room.

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

$$c = c_0\, e^{-\frac{x}{v}t} = c_0\, e^{-Rt} \quad \ldots\ldots (1)$$

where

R = number of air changes in unit time.

Hence

$$\log_e c = \log_e c_0 - Rt$$

Thus by plotting the logarithm of the concentration against time, the rate of air change is obtained from the slope of the line best fitting the points. Examples of decay measurements are shown in Figs. 1 and 2.

Various techniques have been used in the measurements by different investigators. Gases and vapors have been used as tracers, and physical and chemical methods of analysis have been used for estimation of the concentration. The technique adopted at the Building Research Station is one first used by Marley[9], who used a gas (usually helium or hydrogen) as the tracer; its concentration being measured by a katharometer[10,11] (or thermal conductivity meter) and recording galvanometer. This technique has been adopted mainly because of its suitability for continuous electrical recording of the concentration of the tracer, and also because a gas rather than a vapor was preferred as a tracer for general use; thus

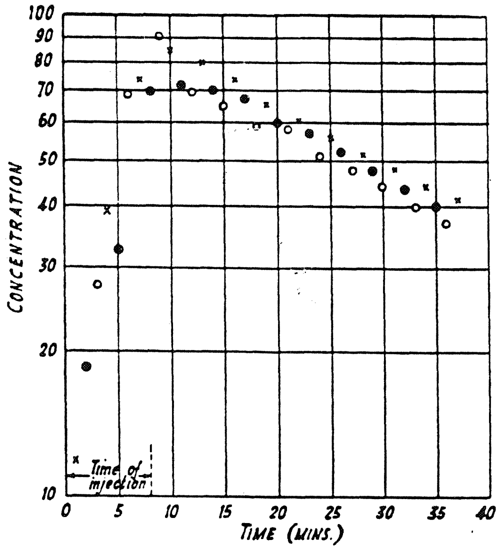


Fig. 1—Concentrations of tracer gas measured at 3 points in a room during a distribution test

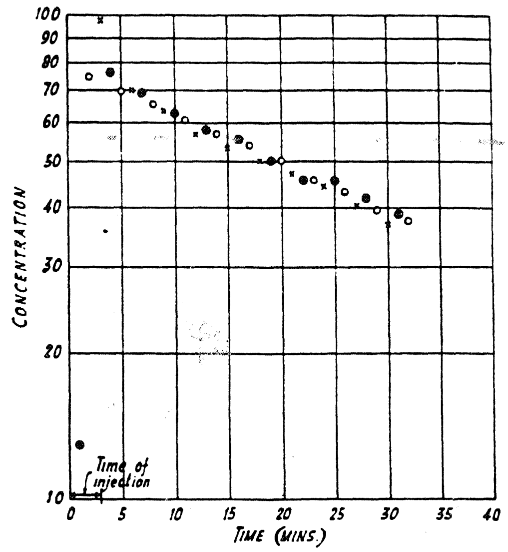


Fig. 2—Concentrations of tracer gas measured at 3 points in a room during a distribution test

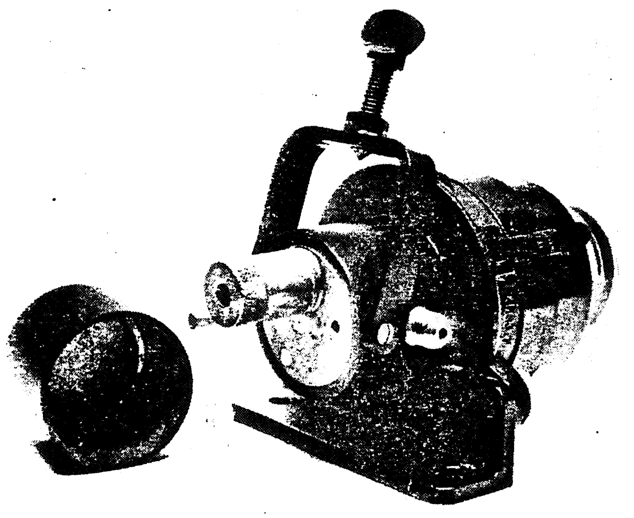
reducing any possibility of absorption or condensation.

In a katharometer, a platinum spiral mounted centrally in a small cell in a metal block is heated by a constant electrical current. As the convection currents are small, the rate of heat loss from such a spiral is very closely proportional to the thermal conductivity of the gas surrounding it, and thus the introduction of a tracer gas, whose thermal conductivity differs from that of air, will change the rate of heat loss from the spiral and hence its temperature and resistance. This change in resistance is usually measured by making the spiral one arm of a Wheatstone bridge circuit; for small concentrations the output is proportional to the percentage of tracer gas present. The instrument is very sensitive, a 7-ohm bridge giving an open circuit output of 10 millivolts for 1 percent hydrogen in air. With the recording galvanometer used (resistance 40 ohms, sensitivity 40 microamps for full scale deflection) it is thus possible to detect the presence of 1 part hydrogen in 10,000 parts of air. Other gases suitable for use as tracers include helium and carbon dioxide which, although they only produce 0.64 and 0.13 times the output given by hydrogen for a given percentage of gas in air, have the advantage of safety. For use in occupied houses helium has therefore been adopted as a tracer in preference to the hydrogen which was used by Marley in his original experiments.

Fig. 3 shows the type of katharometer used. In this type the gas enters the sampling cell by diffusion through an absorption chamber containing a drying agent (a process which for hydrogen has a time constant of the order of 20 to 30 sec and thus does not appreciably affect the measurement of normal rates of air change). When using helium or hydrogen as the tracer, the effect of background variations of carbon dioxide content may be minimized by using soda asbestos in the absorption chamber. These instruments have a slight temperature coefficient, a change of 1 deg in the ambient temperature giving an output equivalent to that produced by about 0.01 percent hydrogen, so that in order to take full advantage of the sensitivity, it is desirable to have the katharometer in a thermostatically controlled chamber. The chamber was omitted when making mobile measurements in rooms, the katharometers being used with caps removed as shown. When concentrations were measured in samples of air withdrawn from the rooms, the katharometers were installed in a thermostatically controlled cabinet, and the samples of air were drawn through the fitted caps past the ends of the absorption chambers, the entry of gas into the cells being completed by diffusion.

In an air change measurement in an unoccupied room, sufficient hydrogen is introduced into the room to give an initial concentration of about 0.2 to 0.3 percent. A fan is operated until the air and gas are mixed, after which the fan is stopped during the measurement of the decay. The concentration of tracer gas is initially measured by several katharometers spaced throughout the room; if the variation in measured decay rate at different locations is small, then, for similar conditions of temperature etc., the subsequent measurements are made using a single katharometer placed centrally in the room.

In the houses investigated in the heating tests, the variation in decay rates at different locations was small except in the space comprising entrance hall, stairs to upper floor and passage upstairs. The convection currents produced by the heating appliances and walls and windows with surface temperatures differing from that of the room air were sufficient to maintain adequate circulation within the square or rectangular rooms, but



(Shows absorption chamber through which gas diffuses into the sampling cell)
Fig. 3—Katharometer with cap removed

the currents were not sufficient to be effective in the hall and irregular spaces.

The technique described has been extended to meet the requirements of the present experiments, but it should be noted that other tracers and methods of measurement could well be used; for instance, a radioactive tracer gas might be suitable.

The Components of Air Change and Consequent Heat Loss

It will be seen that the air change rates obtained yield only 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 determining the adequacy of ventilation in a room (the air coming from adjacent rooms may or may not be contaminated) and when estimating the heat lost by ventilation from a room or a building.

Since the rate of air flow from a room is equal to the air flow into a room, the air balance equation for a room in a house with n rooms may be written

$$\sum_{r=2}^{n} x_{1-r} + x_{1-o} = \sum_{r=2}^{n} x_{r-1} + x_{o-1} \qquad \text{..................(2)}$$

where

x_{1-r} = rate of air flow from room 1 to room r.

x_{r-1} = rate of air flow from room r to room 1.

x_{1-o} = rate of air flow from room 1 to outside.

x_{o-1} = rate of air flow from outside to room 1.

Equation 2 neglects the effect of change of volume with temperature but this effect is usually small compared with the inherent variance of ventilation measurements.

The rate h at which heat is lost from the room by the flow of air is:

$$h = s\left[\sum_{r=2}^{n}(x_{1-r}T_1 - x_{r-1}T_r) + x_{1-o}T_1 - x_{o-1}T_o\right] \qquad \text{.......(3)}$$

where

s = volume specific heat of air.

T_r = temperature of air in room r.

T_o = external temperature.

and the rate h_1 of heat loss from the room to outside alone is

$$h_1 = s[x_{1-o}T_1 - x_{o-1}T_o] \qquad \text{.......(4)}$$

Again this is an approximation as it neglects changes in humidity. It also assumes that the air leaving a room is at the mean room temperature, and thus does not make any allowance for heat gained by air as it passes up a heated flue—a heat interchange which is normally included in the overall efficiency of a heating appliance.

The rate H of heat loss from the house due to exchange of air with the outside is a summation for all rooms (using equation 4):

$$H = \sum_{r=1}^{n} s\,[x_{r-o}\,T_r - x_{o-r}\,T_o]$$

and since

$$\sum_{r=1}^{n} x_{r-o} = \sum_{r=1}^{n} x_{o-r}$$

the rate of heat loss H is

$$H = s\sum_{r=1}^{n} x_{r-o}\,(T_r - T_o) \qquad \text{.......(5)}$$

an expression which does not directly involve the interaction components between rooms.

Using a Tracer Gas to Determine the Components of Air Change and Consequent Heat Loss

1. *Ventilation of Rooms:* 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 determined from the concentration of tracer gas in the second room. It was found in the experimental houses that this type of air 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 rooms was obscured 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_{1-2}, the equations for the concentration of tracer gas, using the nomenclature previously defined, are

$$-v_1\frac{dc_1}{dt} = (x_{1-o} + x_{1-2})\,c_1$$

$$-v_2\frac{dc_2}{dt} = x_{2-o}\,c_2 - x_{1-2}\,c_1$$

where

v_1, v_2 = volumes of rooms 1 and 2.

c_1, c_2 = concentrations of tracer gas in rooms 1 and 2, respectively.

At time t, and with the initial conditions of $c_1 = c_o$, $c_2 = c_o'$ at $t = 0$ the solutions are

$$c_1 = c_o\, e^{-\frac{x_{1-o} + x_{1-2}}{v_1} t}$$

$$c_2 = c_o \frac{x_{1-2}}{v_2} \frac{1}{\left(\frac{x_{2-o}}{v_2} - \frac{x_{1-o} + x_{1-2}}{v_1}\right)} \times \left[e^{-\frac{x_{1-o} + x_{1-2}}{v_1} t} - e^{-\frac{x_{2-o}}{v_2} t} \right] + c'_o\, e^{-\frac{x_{2-o}}{v_2}}$$

In practice, by sealing the cracks or ventilator (through which flow is occurring to room 2), while the tracer gas is mixed in room 1, the concentration in room 2 is zero when the decay starts in room 1. Assuming therefore that $c_o' = 0$, if R_1 and R_2 are the prevailing rates of air change in rooms 1 and 2 (equal to $\frac{x_{1-o} + x_{1-2}}{v_1}$ and $\frac{x_{2-o}}{v_2}$ respectively), the equations for the concentrations may be written:

$$c_1 = c_0\, e^{-R_1 t} \quad \text{..................... (6)}$$

$$c_2 = c_0 \frac{x_{1-2}}{v_2} \left(\frac{1}{R_2 - R_1}\right) \left[e^{-R_1 t} - e^{-R_2 t} \right] \quad \text{..................... (7)}$$

Hence when R_1 and R_2 are known, the shape of the leakage curve (*i.e.* c_2) may be calculated from Equation 7 and compared with the measured concentrations. By plotting the concentrations on a logarithmic scale against time, the multiplying factor $c_0 \frac{x_{1-2}}{v_2}$ and hence x_{1-2} 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 since the maximum occurs when

$$R_1\, e^{-R_1 t} = R_2\, e^{-R_2 t}$$

or

$$t = \frac{1}{R_1 - R_2} \log_e \frac{R_1}{R_2}$$

and hence, from Equation 7

$$c_{2(max)} = c_0 \frac{x_{1-2}}{v_2} \frac{1}{R_2 - R_1} \times \left[\left(\frac{R_1}{R_2}\right)^{\frac{R_1}{R_2 - R_1}} - \left(\frac{R_1}{R_2}\right)^{\frac{R_2}{R_2 - R_1}} \right] \quad \text{..................... (8)}$$

and

$$\frac{x_{1-2}}{v_2} = \frac{c_{2(max)}}{c_0} \times \frac{R_2 - R_1}{\left(\frac{R_1}{R_2}\right)^{\frac{R_1}{R_2 - R_1}} - \left(\frac{R_1}{R_2}\right)^{\frac{R_2}{R_1 - R_2}}} \quad \text{..................... (9)}$$

In the unoccupied phase before taking an air change measurement in a room, the direction of the air flow through ventilators or cracks around the closed doors to adjacent rooms was determined, using smoke as a tracer; if leakage occurred to an adjacent room, then the subsequent concentration in that room was recorded. When the series of measurements in the rooms had been completed, the air change rates in individual rooms were correlated with the relevant variables (such as wind speed and direction, and temperature difference between internal and external air) and the prediction equations formed. Thus, when examining the leakage which had been recorded during a particular measurement, the air change rates in the two rooms were known, (one by measurement and the other from the prediction equation), so that either of the two methods indicated could have been used to determine x_{1-2}. The second method of comparing maxima, being simpler, was adopted for general use. Knowing the air flow between rooms and the total air change rate in the room, the components of air change could be calculated from Equation 2. Hence when determining the adequacy of ventilation, the replacement air entering a room could be divided into air entering from outside and air entering from the remainder of the house. Similarly when concerned with heat loss by air exchange, the amount of air leaving a room could be divided into the air passing directly to outside and that passing to the remainder of the house, so that the total rate of heat loss from the room could be calculated from Equation 3 and the rate of heat loss from the room to outside calculated from Equation 4.

As an example of the type of measurement previously described, the leakage concentrations observed in a room (room 2) during an air change measurement in an adjacent room (room 1) are shown in Fig. 4. In room 1 the initial concentration was 20 units and the measured rate of air change (R_1) was 2.0 per hour; the rate of air change in room 2 (R_2) was estimated from a prediction equation to be 3.6 per hour. The theoretical curve for the function $c_2/c_0 \frac{x_{1-2}}{v_2}$ was calculated by substituting these values of R_1 and R_2 in Equation 7, and by plotting this function and the observed concentrations on a logarithmic scale and then superimposing as previously described, the multiplying factor $c_0 \frac{x_{1-2}}{v_2}$ was estimated to be 17, and as $c_0 = 20$ hence $\frac{x_{1-2}}{v_2} = 0.85$

To obtain a good agreement between observed and calculated curves, a time delay of 4 min in the recorded concentrations had to be assumed. The calculated curve, assuming that $c_0 \frac{x_{1-2}}{v_2} = 17$ and that there is a delay of 4 min, is shown as the full line in Fig. 4. It will be seen that agreement is good apart from the initial portion 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 to secure agreement of the concentration curves. The process described for calculating the theoretical curve and superimposing it on the observed results has therefore been repeated, on the assumption that there is a time constant of 4 min for the mixing process in room 2. The estimated value of $c_0 \frac{x_{1-2}}{v_2}$ was found to be 17, and as will be seen from the dotted line in Fig. 4 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 displace-

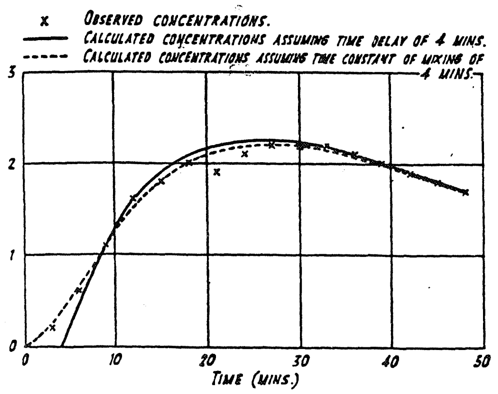


Fig. 4—Example of leakage of tracer gas to an adjoining room

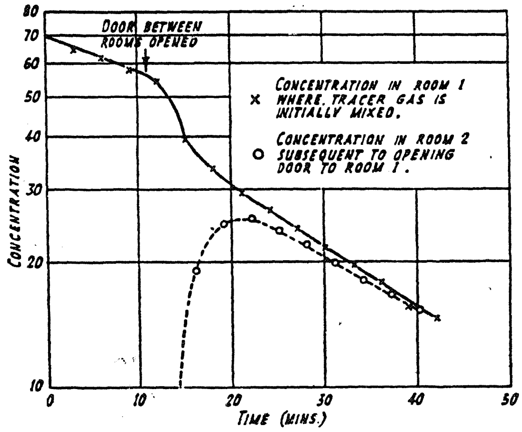


Fig. 5—Example of recirculation between two adjoining rooms

ment in time. Hence, it is valid when superimposing to neglect the initial measured concentrations and displace the curves in time, if this is necessary to obtain a good fit.

Using the routine method of comparing maxima (the observed value and that calculated from Equation 8) the value of $c_0 \frac{x_{1-2}}{v_2}$ in the foregoing example was again estimated to be 17.

2. *Recirculation between Rooms:* When an internal door between two rooms in a house is open, a small temperature difference will cause a considerable amount of recirculation of air to occur between the rooms. This recirculation can be investigated using a tracer gas by mixing the tracer with the air in one room with the door closed, and then opening the door and measuring the subsequent concentrations of tracer in the two rooms; due allowance being made, if required, for the change in density of the air due to the presence of the tracer.

An example of this type of measurement is shown in Fig. 5. In this example interchange between the rooms was rapid, and after the door between them had been opened, the mean concentrations of tracer gas in the two rooms (measured as the average of 10 sampling points in each room) quickly approached the same value. The final rates of decay in the two rooms were very similar; the two rooms in this case could well have been treated as a single space in regard to air change rate. If the air change rates measured in two rooms coupled in this manner do differ appreciably, the rate at which the air in the two rooms is replaced may be obtained from the measured rates of decay when the concentrations of tracer gas in the two rooms are equal.

3. *Whole House Measurements:* The results of a series of measurements of ventilation rates and leakages in rooms of an unoccupied house, in which the doors and windows have fixed degrees of opening, may be correlated with the relevant variables such as wind (speed and direction) and temperature differences, and hence the rates of air flow may be predicted for given values of these variables. It is thus possible by summation throughout the house to estimate the rate at which air enters (or leaves) the house for particular conditions of the controlling variables. Similarly, the rate at which heat is lost from the house by ventilation may be estimated from Equation 5.

When the house is occupied and the tenant is in complete control, the opening of particular doors and windows (which may change at any time) will occur in a range of combinations imposed by the tenant. This large increase in the number of controlling variables makes it practically impossible to correlate the observed rates of air exchange with the outside, and heat loss to outside, by a procedure similar to that adopted in the unoccupied house. Further, the conditions within the house can no longer be considered as subject to small variation throughout the period of a measurement; in particular, internal doors being opened and closed may change the interaction between two rooms from a unidirectional flow to a recirculation or vice versa.

However, if a tracer gas is introduced into the n rooms of a house, the concentrations in the rooms being $c_1, c_2, \ldots, c_r, \ldots$, then the rate G at which the tracer gas leaves the house is

$$G = \sum_{r=1}^{n} x_{r-o}\, c_r \quad \text{.............. (10)}$$

The rate H at which heat is lost from the house by ventilation is given by Equation 5. Comparing Equations 5 and 10, if

$$c_r = y(T_r - T_o)$$

the rate of loss of tracer gas = $y/s \times$ (rate of loss of heat) or

$$G = \frac{y}{s}(H)$$

Thus when the concentrations of tracer gas in the rooms are proportional to the corresponding difference between the room and external temperatures, the rate at which heat is lost by ventilation may be obtained from the measured rate of loss of tracer gas. Similarly, the air flow to outside may be obtained from the rate of loss of the tracer gas when the concentrations in the rooms are equal. The method by which measurements of this type have been made in the occupied experimental

Fig. 6—Copper tubes used for introducing tracer gas and extracting air samples

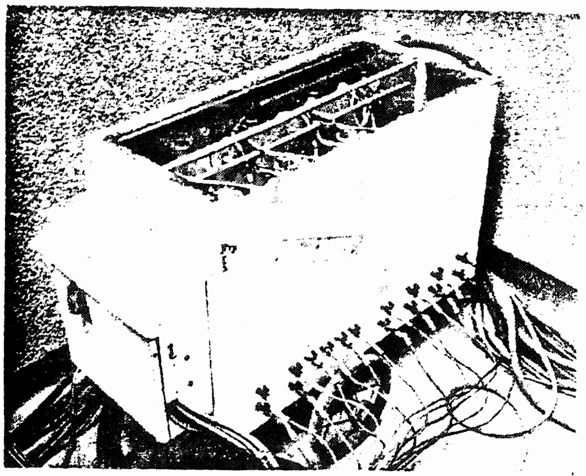


Fig. 7—Mobile trolley in which katharometers are housed

houses is described in the section following.

Method Used for Ventilation Measurement in the Occupied Houses

In the heating tests as a whole the experimental technique has been designed to avoid interference with the life of the tenant; for instance, room temperatures (air and globe), humidity, window and door opening are all remotely recorded. The technique developed for measuring ventilation in the occupied houses has been fashioned by this requirement, and in its final form allows the measurements to be made without any interference with the tenant, the process being remotely controlled and recorded.

In the experimental houses, a series of ¼ in. copper tubes were installed to permit introduction of a mixture of tracer gas and air from outside to any room; the run and termination of these tubes outside the house is shown in Fig. 6. In each room a tube is mounted on the baseboard around at least three sides of the room and is fitted with blocks (at foot intervals) which are threaded to take motor cycle carbureter jets, the delivery from the jets being horizontal and perpendicular to the wall on which the tube is mounted. The distribution of tracer gas within the room is achieved by sizing the jets according to their position in the supply line (to allow for pressure drop along the tube), and according to the volume of the room served by them—for instance, the jets are smaller in the corners of the rooms. Mixing of the tracer gas with the room air is due partly to the turbulence produced by the jets, but mainly to the entrainment of the tracer in the air currents in the room, there being 30 or 40 jets per room. The distribution is determined by using portable katharometers spaced throughout the room: the results of two tests are shown in Figs. 1 and 2. In these tests the time of injection is usually about 5 to 10 min for helium which was introduced at a concentration of 10 to 20 percent in air, but these values are not very critical as will be seen from the example in Fig. 2 where satisfactory distribution was obtained with a 3 min injection using 60 percent helium in air. In this connection a recent experiment by Lidwell[12] provides an extreme example. He liberated suddenly at a point in a room of 4500 cu ft volume, a quantity of acetoacetic ester vapor and found the circulation time in the room to be about 4 min. After 20 min the vapor was fairly uniformly mixed with the air in the room. Obviously the limits for the time of injection, and the concentration of tracer gas in the incoming mixture which may be used, will depend on the number of points used for injection, the magnitude of the convection currents and the period of circulation of the air masses in the room. These limits have not been investigated in detail in the present experiments in which an empirical approach has been adopted.

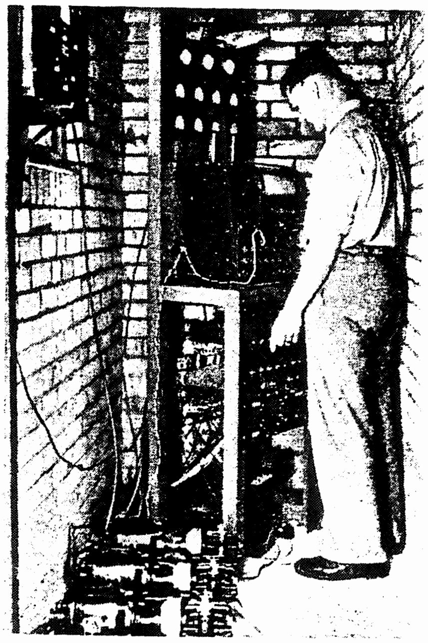


Fig. 8—Recorder hut containing remote controls

A second set of copper tubes was installed in the houses so that a continuous sample of the air in each room may be withdrawn by a vacuum pump and the concentration of tracer gas measured by katharometers. Spaced throughout each room are eight or [illegible]