MEASUREMENTS OF AIR MOVEMENTS IN A HOUSE USING A RADIOACTIVE TRACER GAS*

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SYNOPSIS

Experiments are described in which a radioactive gas (^{85}Krypton) was used to measure the air movements occurring in a typical, detached, suburban house. The air change rates which took place in single rooms with their doors shut and heating by either central heating radiators or open fires were first measured. These tests showed that excessive air changes occurred with the ordinary open fire, but that these were reduced to a level normally regarded as desirable by using a freestanding convector fire with restricted throat.

When the rooms were heated by hot water radiators, excessive air changes still occurred unless the chimney was sealed or a freestanding convector fire with its throat restrictor at its maximum closure was installed. With either of these conditions, however, rates of air change were near the optimum for good ventilation.

The effect of leaving the doors of all the rooms open with all the windows shut was also investigated. It was found that when the downstairs rooms only were heated very large air flows took place from these rooms to the upper storey, and circulation rates of up to 16 000 cu ft/h from each of the downstairs rooms were found. By means of temperature measurements, it was shown that these air movements caused large heat transfers to the bedrooms if the bedroom doors were left open. If, however, the bedroom doors were shut (as they normally would be, even in an "open-plan" house), or if an upstairs landing window was left open, very little warming of the bedrooms took place, and considerable heat losses occurred through the open window.

An investigation was also made into the behaviour of a forced-circulation ducted warm-air system, which was of the type in which ducting was not provided from each room for the return air. It was shown that with the doors closed much of the warm air put into the rooms escaped through the windows even when these were "closed".

1. INTRODUCTION

THE role played by ventilation in the creation of a comfortable environment is perhaps more clearly understood than many of the other factors affecting comfort. There is very little dispute about what constitutes adequate ventilation, and most workers are prepared to accept the standards formulated by the Ridley Committee.[1] In fact these standards are so well established that, in designing heating systems, it is commonly assumed that they will be implemented by the user, and corresponding allowances are made for the heat losses that would result from these ventilation rates.

This procedure in itself is commendable, but unfortunately in most heating systems there are no means of ensuring that the design ventilation rate is achieved. Instead, the user is assumed to adjust the ventilation to its optimum rate by the relatively crude means at his disposal, such as opening windows. In practice it is unlikely that the ventilation rate actually occurring will be that for which the system was designed and this may have an unfortunate effect upon the thermal performance.

Any investigation of room and house heating should therefore first examine the ventilation rates which are likely to be achieved in practice. The results of this investigation can then be used to assess the value of the existing arbitrary design allowances.

However, this is not the only problem requiring investigation. In designing heating systems it is assumed that all the air for ventilation is drawn from outside the house, and that after being heated to the temperature of the room this air is returned from that room to outside. It seems most unlikely that this does in fact occur. In a

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room without a flue it is much more likely that air flows through the room between doors and windows under the influence of thermally or wind-induced pressure gradients. It is thus extremely likely that the ventilation for some rooms will consist mainly of air expelled from others. This has two important effects:

First, the physiological requirements for fresh air may not be satisfied, so that even though the rate of air change may be quantitatively sufficient, ventilation in the true sense may be inadequate. Secondly, and of greater importance from the point of view of this Paper as it is principally concerned with thermal effects, significant heat transfer may occur because of the movement of warmed air from room to room in the house. In fact, it is unlikely that a completely satisfactory design basis for heating systems will be achieved until this factor of heat transfer from air movement is fully taken into account.

These considerations apply particularly to houses in which the inside doors are left open, where basic principles suggest that large air movements to and from the upper storeys must occur, with consequent heat transfer. Indeed, it is implicit in the design of some heating systems that these heat transfers will be sufficient to enable the whole house to be heated from a centrally placed unit on the ground floor.

Thus, measurements of air movement in these cases can supply essential information, and are in fact a necessary adjunct to room temperature measurements when assessing the practicability of certain heating systems. It must also be remembered that air movement is influenced by heating, and may sometimes result solely from heating. In the simplest case, the provision of an open fire can cause a large air flow through the room and into the chimney. As discussed in the previous paragraphs, much more complex situations may arise when heating on the ground floor causes a convection stream to the floor above. It is necessary, therefore, to study not only the heating caused by air movements but also the air movements which result from heating.

Surprisingly little work has been devoted to these various problems. A number of workers have studied the rates of air change which occur in single rooms, both with and without flues.[2] Dick,[3] in the Abbots Langley experiments, made a comprehensive investigation of the air changes occurring in whole houses but nothing has been published on the important problem of measuring air movements within a house, which suggests that no such work has been done.

This is primarily because, until recently, there have been no suitable methods for carrying out this kind of test-work. Several methods exist for the measurement of chimney flows in the laboratory but these are not suitable for tests in a house. In occupied rooms, air velocities through the fireplace opening have been measured by means of anemometers or velometers, and chimney volume flows computed from the results.[4] Measurements of this type have been made for many years and have provided useful data on the amount of air drawn through a room by various types of fire, as well as the influence of chimney height.

It must be made clear, however, that chimney volume flow and room air change are not necessarily synonymous; an obvious example of this is the type of fireplace which draws most of its air supply from beneath the floor of the room. Even with fires of more conventional design, it is possible to have a direct draught between room inlet and exit (between, say, the bottom of a door and the flue) which, though it would be recorded as part of the chimney volume flow, might make practically no contribution to the room air change. The converse can also occur; for example, there can be ventilation caused by a cross-draught between a window and a door which is additional to that caused by the chimney flow.

These air movements in a single room, and those which occur within a house as a whole, can be studied if the air is "labelled" with a tracer of some kind. The substance used for this purpose should:

(*i*) mix readily and evenly with air;

(*ii*) not be lost by absorbtion;

(*iii*) be easily measured;

(*iv*) be harmless to both personnel and furnishings.

Providing mixing is complete and the tracer is confined to one room, the kinetics of the decrease in concentration are those of a first-order reaction, and the rate of air change can be calculated from the formula

$$\log_e \frac{c_o}{c_t} = Nt$$

where: N = number of room volume changes per unit time

c_o = initial concentration

c_t = concentration at time t

t = time period.

The rate of air change is then given by VN, where V is the volume of the room.

The use of tracer techniques to measure the air changes in single rooms is not new. A century ago Roscoe[5] released carbon dioxide into a room and measured the rate at which its concentration decreased. This method has serious disadvantages. In order to achieve an accuracy of 10 per cent. in the final measurements, an initial concentration of at least 5 per cent. of CO_2 is preferable and its toxic effects[6] at this level make tests in occupied rooms impracticable. Such concentrations will also affect the rate at which a fire burns and will tend to decrease the rate of flow up the flue. Finally, the method depends on sampling the room air at frequent intervals and making a chemical analysis of the CO_2 in each sample (usually by Haldane apparatus) and this requires a considerable amount of time. Recording CO_2 meters may be used, but these usually entail some loss of accuracy.

Most of these objections were overcome when Marley used hydrogen,[7] and later coal gas,[8] as the tracer, and measured its concentration with a katharometer. This method requires only about 0·3 per cent. of tracer in the air, and this is not sufficient to alter the general conditions. Other tracers which have been used are water vapour,[9] helium,[10] and tertiary-butyl hypochlorite.[11]

The increased availability of radioactive gases in recent years has provided several new, easily detected, tracers suitable for mixing with air. Willax and Maier-Leibnitz used radon as a tracer under laboratory conditions, and by means of a sampling technique[12] were able to show clear distinctions between homogeneous mixing of air currents and displacement ventilation. Recently Collins and Smith[13] showed that a radioactive tracer gas and a continuously recording ratemeter could be used under field work conditions. Of the radioactive gases available, krypton (^{85}Kr) is the most readily obtained and the cheapest. Moreover, it fulfils the requirements for a tracer mentioned above, since adequate sensitivity can be obtained without exceeding the maximum permissible radiation dose.

In essence, the problems associated with the use of a radioactive tracer are very similar to those encountered with chemical tracers. The main difference is that with radioactive tracers the process of sampling is somewhat simplified. An ordinary gas sampling nozzle has a very limited sampling range, whereas, in comparison, the Geiger-Muller tube samples a fairly large volume. Using a tube sensitive to the β radiation, the sampling volume of the counter is effectively a sphere having a 2-ft radius (i.e. a volume of 25–30 cu ft). This tends to render the method less susceptible to small local variations in the tracer concentration. In general the advantages of using a radioactive tracer may be summarised as follows:

(*i*) the withdrawal of a sample and its subsequent analysis are eliminated;

(*ii*) the range of the detector is considerably greater than with any other method;

(*iii*) detector response is instantaneous;

(*iv*) a continuous record of results can be obtained;

(*v*) relatively high accuracy is achieved, with a rapid and uncomplicated technique;

(*vi*) sensitivity is very high and makes measurements possible which could not be attempted with other tracers (e.g. air movement between rooms).

In the course of central heating field trials, it became clear that a study of the air movements associated with whole-house heating was desirable, and it was decided to use a radioactive tracer gas in an unoccupied experimental house to study both these and the air movements in individual rooms.

2. DESCRIPTION OF THE TEST HOUSE

All the work described in this Paper was carried out in a detached two-storey house, the layout of which is shown in Fig. 1. The total floor area was 1150 sq ft, the walls were of 11-in brick cavity construction, the roof tiled on boards, and the upstairs ceiling insulated with 3-in mineral wool. Both upstairs and downstairs floors were of tongued and grooved boards, which were covered with Kraft building paper, sealed at the joints and edges to simulate linoleum. The window frames were of wood with leaded glass, and they and the doors were of about average fit.

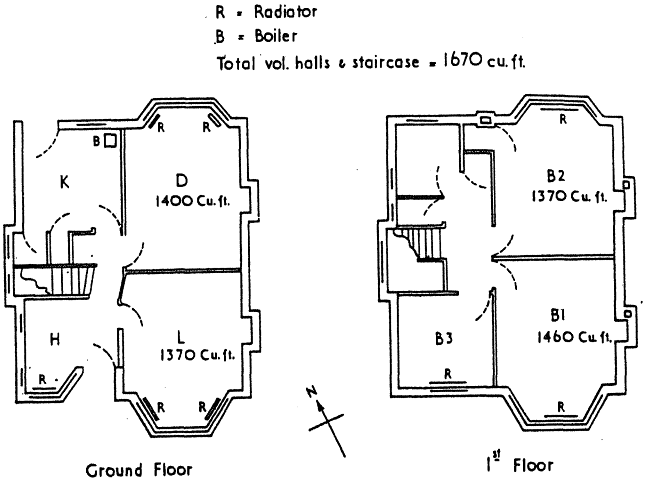

Fig. 1.—Plan of experimental house.

Each of the downstairs rooms had an open fireplace, as had the two main bedrooms (B_1, B_2) with the flues running up the outside wall and terminating well above roof ridge level. A small-pipe central heating system[14] had been installed in the house for experimental purposes, and was available for use as and when required in the ventilation experiments.

Air temperature was measured in each room (and in the hall and landing) by thermocouples connected to a multi-point recorder and also by thermographs. Outside air temperature was recorded by a thermograph situated in a Stevenson screen in the garden. Information on local wind speeds and directions was obtained from a neighbouring weather station.

3. PRELIMINARY EXPERIMENTS

As with all other techniques based upon tracer methods, there were two main problems associated with the use of ^{85}Kr. One was to ensure rapid and complete mixing with the air of the room in which ventilation tests were to be carried out, or which was to be the starting point for whole-house air movement experiments; the other was to place the detector in such a position in the room as to ensure that a representative sample was obtained.

These two problems are to some extent interrelated. If the initial mixing is complete, any randomly selected position will give a representative sample for the whole room. Sampling problems arise only if subsequent air movements are such as to create pockets of air having a smaller or larger concentration of tracer than the average. It is then necessary to take readings with a Geiger-Muller tube at several positions.

Some preliminary experiments were therefore undertaken to assess the extent of these problems for a single room. It was found that the initial mixing depended largely upon the way the room was heated. With a simple open fire there was insufficient convection air movement within the room to ensure adequate and rapid mixing. A large slow-running fan was therefore placed be true that if there were a separate plant one would be able to condition to the state one wanted instead of boosting afterwards. But it would have been more complicated. One should also keep the matter in perspective. The coffee house is a marginal offshoot of what is a very large plant, and in all the circumstances and having in mind the relative size of the coffee house and the main plant, it was not worth doing.

Mr. E. M. Arthur: There are two questions which I should like to ask in connection with the installation. The first is how do the authors reconcile taking a large extract from high level with what is basically a downward form of air distribution? Secondly, have they determined what sort of temperature is obtained at the high-level grille?

Another point which strikes me about the underwriters' room is the fact that the underwriters in their boxes are surrounded by a mass of humanity when they are busy, and I know from observations made on the building just after the war that the boxes are piled up with ledgers and books, so I would have thought that general room distribution would not get to the individual. Some of the underwriters are young men who play rugby and who doubtless like air movement—and probably cool air at that—whereas there are also older men who probably do not like very much movement, and who seize the first opportunity they can to sit over a fire! I should like to know how the authors have been able to adjust what I can well believe is an excellent system of air-conditioning to the varying points of view of the individual.

Mr. J. R. Kell, in reply: With regard to the downward system of distribution with these large extracts at high level, in actual practice if you consider the place as a whole, you will find that the so-called high-level extracts are not really high-level at all. On the other hand, I think one has found that the position of the extract is not very important to general distribution; so long as the air is shifted through the place and the inlet is distributed as well as is possible, I think one can play around with the extract position to a considerable extent without making much difference. It is not possible physically to extract too near to where people are sitting. We could not use the old system of extracting through the boxes for reasons I have explained, and although the "tombs" may stick up some 8 ft high, in proportion to the height of the room they are quite near the floor.

The mass of humanity surrounded by ledgers does seem to get sufficient air movement to keep it alive and awake, which is simply to do with turbulence in the room as a whole. We are changing the air twelve times an hour and this is bound to produce all kinds of secondary air currents.

Dr. T. C. Angus wrote after the meeting:

The interesting introduction to this important Paper by Mr. Kell and Mr. Doe gives heating and ventilating engineers some reason for pride. In spite of all vicissitudes, London has well been called "the Proud City" and is still the world's financial centre. We, as heating and ventilating engineers—"engineers of human comfort" as we have been called by an eminent American—have cause for satisfaction that we help to ease the stress of modern life.

It is extremely interesting to hear that the authors found that air distribution is more effectively controlled by adjustment of temperature than by changing the direction and velocity at air inlets. In his classical work Sir Napier Shaw wrote:

> "The dominant law in the ventilated space is the law of convection. It is at once the condition of success and the cause of most failures. Without convection ventilation would be impossible; in consequence of convection nearly all schemes of ventilation fail",

and this was written fifty-three years ago! I feel that we all owe a debt of gratitude to the authors for not only giving us such detail in the design figures of a first-class installation that was of such an importance that no limit was set to expense, but also for being able to establish the correctness of their designs by critical observation under user conditions over a winter and a hot summer.

In my own research work during the past years the question of air movement over the living occupant has always been of great interest, and I still believe that the importance of this factor in securing comfort is apt to be overlooked. Could the authors give us more particulars of their experiences hinted at on page 39. On the same page reference is made to the ventilation in "another place", where the supply air was designed to be delivered intermittently and alternately from jets on opposite sides of the House. This installation has already been described in our *Journal.* Would it be a "breach of privilege" for us to be told what has been experienced with this unusual, and one would suppose in every way desirable, method of distribution. The authors in this Paper lead us to believe that once more convection has had some unlooked-for effect here?

The authors wrote in reply to Dr. Taylor and D. Angus:

Reference has been made by both Dr. Taylor and Dr. Angus to the nature of the difficulty of persistent air movement referred to in the Paper. This trouble was a persistent air movement from SW to NE over approximately two-thirds the length of the Room, the moving air having no apparent source or destination. After the most far-reaching investigation it was ultimately identified as being due to a slight difference in the control point setting for the east and west plants, causing a large-scale convection current longitudinally within the Room.

The reference to plant losses basically represents the power input to circulating fans, which manifests itself as heat in the air handled and is thus a heat gain for cooling purposes.

The need for reheat arises from the very heavy dehumidification loads in the recirculation plant necessitating some overcooling and consequent reheat. This component of the load is not capable of being dealt with at the fresh air spray chamber.

The acoustic attenuators comprise lined ducts or duct terminals. The results have been found satisfactory, but specific tests on attenuation have not been made, nor is it practical to make them.

in the centre of the room and directed up towards the ceiling, and tests showed that after this had been run for 45 sec, mixing was complete. On the other hand, when there were strong convection currents within the room, rapid and complete mixing was possible without the fan, e.g. it was possible to release the krypton near a radiator and obtain complete mixing within six minutes.

Once complete mixing of the tracer had been achieved, it was necessary to ensure that a sampling position could be found that was representative of the whole room. The tracer concentration was measured at a number of different points within the room with a mobile Geiger-Muller tube and the results showed that, under most conditions, the concentrations at the various points were within 5 per cent. of the mean. This meant that the sampling position was relatively unimportant; for convenience a position in the centre of the room was selected.

However, while this position was undoubtedly representative of the bulk of the room, it would not necessarily show the true effect of floor draughts. These relatively shallow and fast-moving air streams, which occur mainly when a simple open fire is in use, do not diffuse greatly into the room air and thus do not affect the concentration of tracer in the bulk of the room. But, as has been noted, they cannot be held to constitute ventilation in its true sense, and they only assume importance with this type of appliance.

The final problem to be investigated in the preliminary tests was the method of releasing the krypton into the room. The concentration necessary for adequate sensitivity was about 2·5 millicuries.

Once this was diluted in the room air, the radiation dose received during a few hours' exposure was well below the maximum permissible level (0·3 rads/week) but it was considered undesirable to subject the operators to the risk of inhaling concentrated radioactive material during the release period, i.e. before mixing was complete. Moreover, some tests were planned in which opening the door for the operator to go out after the release of the tracer would upset the conditions under investigation, so that if the tracer were released manually the operator would not be able to leave the room.

An apparatus was therefore designed which enabled the krypton to be released remotely. This is illustrated in Fig. 2. The reservoir was held below the water level in the gas sample tube while the tap was opened; it was then raised to expel the gas. If an open fire was in use the fan was run for 45 sec after the gas had been released. Otherwise, the krypton was released in front of a radiator and mixed by the convection streams from it.

The radiation counter and recorder were started immediately the tracer was released, and a record of concentration against time was obtained. From this it was possible to calculate room air change in the manner described in the *Introduction*. Inspection of the trace of concentration against time also enabled the point when mixing was complete to be determined.

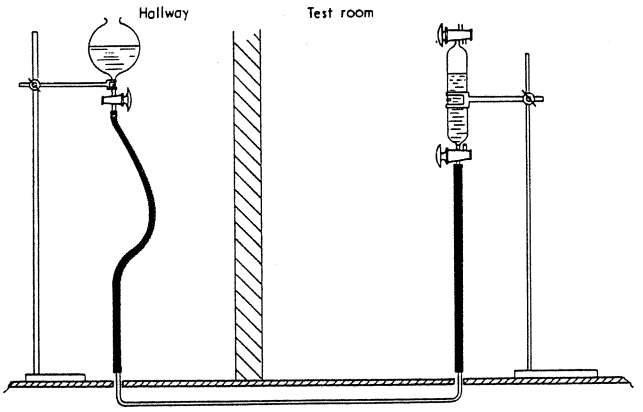

Fig. 2.—Apparatus for releasing ^{85}Kr into room.

4. RATES OF AIR CHANGE IN SINGLE ROOMS

As has been explained in the *Introduction*, the rates of air change which occur in single rooms are of considerable importance in central heating design. The aim of the experiments described in this section was therefore to determine these ventilation rates for various conditions, and also to examine the ventilation rates caused by certain types of open fires. The results are of interest not only intrinsically but also when considered together, since open fires are sometimes used in conjunction with central heating systems.

4.1 Heating by Open Fires

Two types of fire were used in the experiments; a simple inset open fire, and a freestanding convector fire of a type extensively used in previous field trials.[4] In most of the tests the experimental procedure was the same as that described in Section 3 but with certain variations in order to widen the scope of the investigation.

The main additional measurement was a separate determination of chimney flow, using a velometer to find the mean linear velocity of air flow through the fireplace opening. This was thought necessary since, as previously explained, rate of air change and chimney flow are not necessarily synonymous. Further to this, a test was carried out with the ordinary open fire, in which the fan used for mixing the tracer was on throughout the period of measurement. It was hoped this would ensure that the floor draught would be mixed with the body of the room air. Before the test was made it was proved by velometer readings at the fireplace opening that the operation of the fan did not affect chimney flow.

Finally it was thought interesting to compare the krypton method with the normal CO_2 decay procedure. Accordingly, CO_2 was released in the room during some of the krypton tests, and samples taken at appropriate time intervals. The subsequent analysis of these samples permitted rates of air change to be calculated.

The results of these various tests are shown in Table I. Considering the column which gives the rates of air change measured by the krypton method, it will be seen that the results for the ordinary inset open fire are of the order which would be expected. This is not the case, however, with the freestanding fire. Here the ventilation rates are generally somewhat greater than those previously reported. The reason for this becomes clear when

Table I.—Rates of air change with an open fire in room L (door closed).

Test No.	Type of Grate	Conditions					Results		
		Flue Restricted to (sq in)	Transom Window (40 sq in)	Mean Temperature Difference Inside-outside (deg. F)	Wind Speed (m.p.h.)	Wind Direction	Rate of Air Change (cu ft/h)		Chimney Volume Flow (Velometer) cu ft/h
							^{85}Kr	CO_2	
1	Inset Grate	Unrestricted	Closed	16·5	8–12	S	5800	—	6800
2		Unrestricted	Closed	16	8–12	S	7000*	—	6700
3		Unrestricted	Closed	20	5–7	W	7950	7300	9150
4		Unrestricted	Closed	20	5–7	W	—	7000	—
5		Unrestricted	Open	17	5–7	W	10 450	10 450	11 000
7	Freestanding Convector with Restricted Throat	10·5	Closed	13	15–22	SSW	3050	—	1800
8		10·5	Closed	13	5–7	NW	—	3150	—
10		8 (min. opening)	Closed	14·5	6–10	W	2300	—	—
11		10·5	Closed	13·5	6–10	NW	3700	—	3200
12		10·5	Open	14·5	6–10	NW	4200	4600	3000
13		20·3 (max. opening)	Open	27	8–12	W	6750	—	—

* Fan on throughout test.

the rates of air change are compared with the chimney flows. The latter are in fairly good agreement with those measured in the laboratory for this particular appliance, and it may therefore be deduced that the difference between the two flow rates is dependent upon cross-ventilation between door and window, or vice versa.

Such ventilation is quite possible with the freestanding convector fire where the small chimney flow will only cause a small depression in the room static pressure. So long as the static pressure differential between the room and outside is less than that occurring across the room due to wind action, cross-ventilation can take place. It will be shown later that when the flue in the test room was sealed and the windows shut, "cross draught" ventilation of up to 1100 cu ft/h could occur.

With the simple open fire also there is a difference between rate of air change and chimney flow. Here, however, the latter is the greater. This difference is consistent with the theory that the floor draught does not contribute greatly to the air change in the bulk of the room, a theory which is borne out by the results of Test 2, where operation of the fan mixed the floor draught with the room air, thereby causing the rate of air change to be approximately equal to the chimney flow. Thus comparison of the rate of air change and the chimney flow enables the magnitude of the floor draught to be estimated. When the window is shut about 1000 cu ft/h would appear to pass to the fire, without mixing with the room air.

It is interesting to note the effect of opening a transom window upon the rate of air change. With the open fire a considerable increase takes place and all this increased flow went up the flue. With the freestanding convector fire, however, the increase is much smaller and none goes into the chimney. These results provide a graphic illustration of the advantages of an appliance with an integral continuously variable chimney throat restrictor.

Finally it is instructive to compare the results obtained by the two "tracer" methods for a single room. Insufficient tests are available to pass judgment on their comparative accuracy, but on the whole the results agree well. However, the scatter of the individual points when log c_t was plotted against time was very much greater for the CO_2 method than for the krypton tests. CO_2 would, of course, be of little value as a tracer for the excessive dilutions and many sampling points involved in whole-house experiments.

4.2 Heating by Hot Water Radiators

The problem of ventilation allowances for centrally heated rooms has been briefly discussed in the *Introduction*. In general it is assumed that the so-called "Ridley standards" are achieved. These state that each occupant of a room requires 600 cu ft/h of fresh air and therefore, presuming that living rooms will be occupied by four persons and bedrooms by two, living rooms will have a ventilation rate of 2400 cu ft/h and bedrooms 1200 cu ft/h. These figures are broadly in line with those recommended by the *Institution of Heating and Ventilating Engineers*. This body suggests that an hourly allowance, equivalent to 1–1½ times the volume of the room, should be made.

The main object of the work described in this section was to determine how closely these rates are achieved in normal practice. Unfortunately "normal practice" is difficult to define, particularly for houses which have not been built with central heating in mind. Such houses are usually supplied with open fireplaces, and it cannot be assumed that these will be sealed when central heating is installed. Any investigation into room air change must, therefore, take this into account.

The series of experiments were therefore designed to cover a reasonably wide range of conditions and particular attention was paid to the effect of the chimney upon ventilation rates. The door of the room under investigation was kept closed throughout the tests, as this was the only means of preventing room-to-room circulation which was to be investigated separately. Moreover, previous field tests in central heating had shown that internal doors were left open only in exceptional circumstances.

The following conditions were investigated:

(*a*) One transom window open (approximately 40 sq in free area) and open fire flue unsealed.

(*b*) As (*a*) but with fireplace opening completely sealed.

(*c*) Windows shut and the fireplace opening unsealed.

(*d*) As (*c*) but with fireplace opening completely sealed.

(*e*) A freestanding fire was installed but not in use. Tests were carried out with the throat damper fully open and also closed to the minimum opening, and with the transom window open and shut.

Throughout these tests, the rooms in the house were all maintained at their respective design temperatures. Standard experimental procedure was adopted throughout, the tracer being released in front of one of the radiators and allowed to mix by the normal convection circulation. Altogether thirty-seven tests were carried out, spread over several weeks. Inevitably conditions varied over this period and consequently the comparison of results is not easy. Fortunately no great changes in wind speed or direction occurred, the main variations being in the inside-outside temperature differences.

It is convenient to consider the results in groups. Table II gives those obtained for the various rooms when all the windows were shut and the flue was unsealed, and it is clear that, in all cases, the rate of air change was greater than that considered necessary for good ventilation.

Table II.—Rates of air change in individual rooms, with doors and windows shut, chimney unsealed (unlit inset grate) and central heating

Test No.	Room	Mean Inside-outside Temperature Difference (deg. F)	Wind		Rate of Air change (cu ft/h)
			Speed (m.p.h.)	Direction	
1	L	25	10–15	S	3900
2		34	7–10	SW	3950
13	D	34	7–10	SW	4250
16	B_1	8	7–10	W	2900
17		19	10–15	S	2550
27	B_2	11	7–10	W	3050
28		15	10–15	S	3550
29		22	7–10	SW	4000

Table III.—Rates of air change in individual rooms, with doors shut, one transom window open, chimney unsealed (unlit inset grate) and central heating

Test No.	Room	Mean Inside-outside Temperature Difference (deg. F)	Wind		Rate of Air change (cu ft/h)
			Speed (m.p.h.)	Direction	
3	L	26	10–15	S	5700
19	B_1	8	7–10	W	4650
20		18	10–15	S	3200
18		25	7–10	SSW	3400
30	B_2	11	7–10	W	3650
31		16	10–15	S	4250

When one transom window is opened this discrepancy is increased as there is a general increase in the rate of air change (see Table III). This is particularly noticeable in those rooms on the windward side of the house (B_1 and L) but, to a lesser extent, it also applies to B_2, the windows of which opened on the lee side. This result could be expected, since the windows on the windward side open into a zone of increased pressure and those on the lee into one of somewhat reduced pressure.

It would be expected that an increase of inside-outside temperature difference would bring about an increase in the rate of air change, due to an enhanced chimney pull. In still air conditions this must necessarily occur, but it cannot be deduced from the results quoted in the two tables, since any systematic increase in the rate of air change with temperature is masked by shifts in wind speed or direction.

Table IV.—Rates of air change in lounge with door shut and with an unlit freestanding convector fire and central heating.

Test No.	Mean Inside-outside Temp. Difference (deg. F)	Position of Window	Position of Throat Damper	Wind		Rate of Room Air Change (cu ft/h)
				Speed (m.p.h.)	Direction	
9	15	Open	Max. Open	7–10	W	4700
8	33			7–10	SSW	6850
11	15	Open	Max. Closed	10–15	W	2050
7	16·5	Shut	Max. Open	7–10	W	3150
10	15	Shut	Max. Closed	10–15	W	2050

Table V.—Rates of air change in individual rooms with doors and windows shut, chimneys sealed and central heating.

Test No.	Room	Mean Inside-outside Temperature Difference (deg. F)	Wind		Rate of Air change (cu ft/h)
			Speed (m.p.h.)	Direction	
4	L	25	8–12	S	850
12		37	8–12	SW	1100
5		38	7–10	SW	600
14	D	32	7–10	SW	800
15		37	8–12	SW	1100
23	B_1	8	10–15	W	1350
24		17	8–12	S	1150
22		26	7–10	SW	600
21		28	8–12	SW	600
33	B_2	8	10–15	W	600
35		16	8–12	S	1400
34		23	7–10	SW	600
32		28	8–12	SSW	600

The conditions listed in Tables II and III are those which would occur if an ordinary inset grate were installed in a centrally heated room—a combination that occurs quite frequently in living rooms. Table IV illustrates the effect of a freestanding convector fire in place of the inset grate. The results clearly demonstrate the advantages of the convector fire, provided the throat restrictor is kept at its minimum opening when the rate of air change does not exceed that necessary for good ventilation. With the throat restrictor fully opened, however, rates of air change of the same order as those occurring with the simple open fire take place.

The results so far discussed show that if the chimneys in centrally heated rooms are left open, considerable waste of heat may occur due to excess ventilation. Sealing the chimney results in a great improvement, as can be seen from Tables V and VI. In fact, in the case of the lounge and dining rooms, the resulting reduced rate of air change is clearly insufficient for good ventilation (see Table V) and this is not remedied by opening a single transom window (Table VI). There is, however, no doubt that the opening of other windows would allow the ventilation rate to be increased to the optimum level.

Bedrooms, because of their greater height from the ground, are probably rather more sensitive to variations in wind conditions than the downstairs rooms. The results in Tables V and VI certainly show a rather greater variation in ventilation rates for the bedrooms than for the lounge and dining room. They also illustrate that it might be difficult to avoid exceeding the design ventilation rate of 1200 cu ft/h when one transom window is open. The departures from the design ventilation are not excessive, however, and as bedrooms are maintained at a lower temperature than the downstairs rooms, the higher ventilation rates should not result in too great a heat loss.

When the chimney is sealed it is likely that the main cause of room ventilation is the wind-induced pressure difference, in which case ventilation in the test room could be affected by the opening and closing of doors in other rooms. Two sets of tests were therefore carried out, in which the air change in the lounge with the door shut was measured:

(*a*) with all the doors of the other rooms shut;

(*b*) with them all open.

This was done first with all windows shut and then with one transom open in each room. The results are given in Table VII, and it will be seen that an appreciable increase in the rate of air change occurs when the other doors in the house are opened. All these other doors may be regarded as resistances which are in parallel with each other but in series with that formed by the door of the room under test. The opening of any one could therefore have a considerable effect on air flow through rooms remaining closed.

5. AIR MOVEMENT FROM ROOM TO ROOM

So far attention has been concentrated upon the ventilation in single rooms, but the air movements which occur from room to room within the house are equally important in the design of whole-house heating systems.

In an occupied house doors are frequently opened and sudden movements of air result. Opening the door of a heated downstairs room normally results in a drop in its temperature, but this may represent a transfer of heat to other parts of the house rather than a net loss. The transfer will be greater when central heating is in use and the chimneys are sealed than with open fires whose chimney pull would tend to draw air inwards when the doors are opened.

Table VI.—Rates of air change in individual rooms with door shut, one transom window open, chimney sealed and central heating.

Test No.	Room	Mean Inside-outside Temperature Difference (deg. F)	Wind		Rate of Air change (cu ft/h)
			Speed (m.p.h.)	Direction	
6	L	23	8–12	S	1400
25	B_1	7	10–15	W	2050
26		17	8–12	S	1550
36	B_2	8	10–15	W	900
37		18	8–12	S	1950

Design calculations do not usually allow for the heat transfers resulting from these internal air movements, and this is justifiable for the normal opening and shutting of doors which probably has very little effect on the performance of heating systems. When, however, internal doors are left open for long periods, there are good reasons for supposing that large transfers of heat may occur. It is normal to design systems to give higher temperatures in the downstairs living rooms than in the upstairs bedrooms; the consequent temperature gradient between the two floors must result in convection currents within the house, which will tend to equalise the temperatures; thus, if this convection is not checked by closing the doors of the downstairs rooms, the bedroom temperatures will increase at the expense of those in the living room.

Table VII

Condition	Rate of Air Change (cu ft/h)		Increase (per cent)
	Doors Shut	Doors Open	
All windows shut ..	900	1450	60
Transom open in each room including L ..	1750	3100	77

It has been suggested by those advocating simplified heating systems that these internal heat transfers by convection are sufficiently great to enable whole-house heating to be accomplished by installing hot water radiators, stoves or convectors in the downstairs rooms only. Indeed, one of the virtues claimed for houses of the open-plan type is that they facilitate this type of heating. The general practicability of such systems is doubtful, however. The heat transfer to the upper parts of the house is uncontrolled and will tend to be too great during day-time and evening. Unless the downstairs rooms are heated continuously the warming of the upper rooms will be at a minimum during their night-time period of occupancy.

To summarise—two types of room-to-room air movement are of interest; the first is the "initial surge" which occurs when the door of a downstairs room heated to design temperature is opened, permitting a sudden convection flow to the less warm upper part of the house; the second is the continuous convection which occurs through the permanently open door of a heated downstairs room to unheated upper storeys. This latter type of air movement is interesting, as it not only clarifies the difficulties resulting from the misuse of a system designed on the assumption that the doors will be shut, but also provides a basis for assessing the practicability of whole-house heating from downstairs rooms.

5.1 Description of Experiments

While the tracer technique permits air movements to be measured, these measurements in themselves cannot be used to estimate heat transfer; the temperature of the air must also be known. Therefore, in the following experiments, temperatures were measured at twenty-seven points within the house, attention being concentrated on the staircase well, and on the temperature gradients within individual rooms. The disposition of the thermometers in L, B_1 and the staircase well is shown in Fig. 3.

It was planned to measure the air movements within the house by releasing tracer in one of the downstairs rooms and calculating the room air change by plotting the normal decay curve. So long as all the windows in the house were shut and the flues sealed, it could be assumed that a very large proportion of the rate of air change for the two downstairs rooms was caused by circulation to the rest of the house, and subsequently this was proved to be the case. The procedure was not without difficulties. First the tracer method for measurement of room air change assumes that the tracer, having left the room, does not return. It is safe to make this assumption when dealing with a single closed room, but for this particular series of tests, where the doors would be open, the reverse was true; warm air moving from a heated lounge to upstairs could only be replaced (the lounge window being closed) by cooler air coming down from upstairs; in fact, part of the basis of the tests was the assumption that free circulation around the house would be established. Therefore some preliminary tests had to be made to investigate the nature of this circulation and discover whether there was sufficient time to measure the rate of air change before the readings were invalidated by the re-entry of labelled air into the room under investigation.

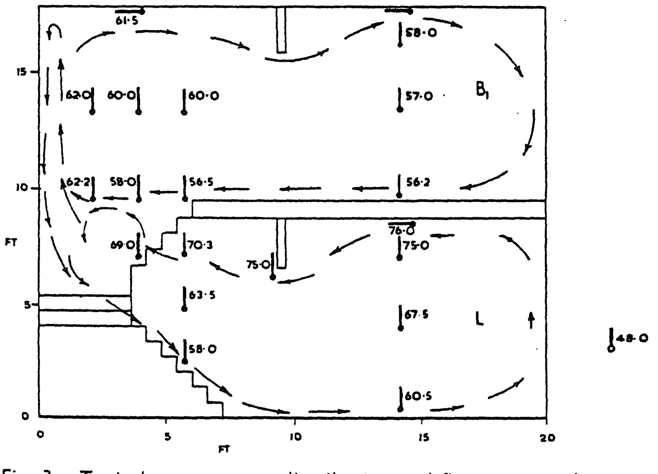

Fig. 3.—Typical temperature distribution and flow pattern, heating in downstairs rooms only.

Exploratory tests had shown that when the doors of the downstairs rooms were open there was a pronounced air flow out of the top half of the door and an equally marked return flow through the bottom half. Similar tests showed the opposite to be true of the bedrooms. In both cases the velocity increased rapidly towards the top and bottom of the doorways. These measurements were consistent with the theory that warm air was leaving the downstairs rooms through the top of the doorways, passing up the stairway, entering the bedrooms via the upper part of the bedroom doorways and then, after cooling, returning to the lounge through the bottom part of the bedroom and downstairs doors (Fig. 3).

To measure the speed of this circulation Geiger tubes were fixed in the doorways of L and B_1 as follows:

(1) top of doorway, room L;

(2) top of doorway, room B_1;

(3) bottom of doorway, room B_1;

(4) bottom of doorway, room L.

Krypton was then released in L near the radiator, and the time was noted when a rise in count rate was detected at each tube. The order in which the tracer reached the detectors was 1, 4, 2, 3, and not, as might be expected, that listed above. This suggested that not all the warmed air was reaching the bedrooms, and smoke traces, together with readings from the thermometers in the stair well, indicated that the pattern of air flow was in fact similar to that shown schematically in Fig. 3. It will be seen that the cooler air returning from the bedroom causes an eddy current, which prevents the warmed air from rising directly up the stair well. Some mixing occurs in the stair well and some of the "labelled" air is cooled and returned to the lounge. It was observed that the cooled air kept close to the stairs, the return stream being 6 to 12 in deep.

The time between the first indication of tracer passing the counter in the top of the lounge doorway and a similar indication at the bottom of the doorway was 2·5 min. Thus, if the circulation of air to the house was to be deduced from measurements of the rate of air change in the lounge, these measurements would have to be completed within 2·5 min; after this time the re-entry of "labelled" air would invalidate the measurements.

The combination of the short time available for the measurements and the considerable air movements which were taking place made it doubtful whether a single Geiger-Muller tube at the centre of the room would give a sufficiently accurate measure of tracer concentration for meaningful results. Experiments were therefore carried out to determine the number of readings necessary to give an accurate measure of tracer concentration in the lounge.

These experiments consisted of mixing the tracer with the lounge air whilst the door was shut, taking the count rate in the room, and then opening the door and permitting the "labelled" air to mix with that in the hall, landing and B_1, all the other doors being shut. Immediately after opening the door, readings were taken with a Geiger-Muller tube at five points each in the hall, landing and B_1 and at three points in the lounge. From these eighteen readings, which because of the rapid response of the detectors could be made sufficiently quickly to allow a mean concentration to be obtained, a "tracer balance" was calculated as follows:

Before opening door: Count rate 35 c/s. Volume 1370 cu ft. Count rate × volume = 47 950.

After opening door: Mean count rate 11 c/s. Volume 4410 cu ft. Count rate × volume = 48 510.

These results vary by less than 1·2 per cent., although some of the individual readings showed variations of ±25 per cent. from the mean. The readings from the three points in the lounge, however, did not deviate greatly from their mean. From these results it was apparent that three sampling points in the lounge would enable the mean concentration to be measured with sufficient accuracy for a rate of air change to be calculated. The points selected were 1 ft 6 in above the floor, 1 ft 6 in below the ceiling, and a point midway between—all three being at the centre of the room.

One further factor remained which might have invalidated the results. To obtain adequate mixing of the tracer by natural convection the door of the room under investigation had to remain shut for between four and six minutes (the fan could not be used to promote rapid mixing as this would have upset the natural temperature gradients within the room). When the circulation under investigation was that occurring when the door was permanently open, there was a danger that closing the door, for even this short time, might affect the general pattern of air flow by altering the stable temperature distribution in the rest of the house.

Investigations showed that no measurable alterations occurred during the time the door was shut. This can be attributed mainly to the fact that the door of either lounge or dining room was always open and the flow from the open door was sufficient to maintain the broad pattern of the circulation.

These preliminary investigations showed it would be possible to obtain a significant result, so the full-scale experiments were started. In these tests the lounge and dining room were maintained at design temperature and the heating in the rest of the house was turned off (i.e. the same conditions as had been maintained throughout the preliminary experiments). The radiators in the lounge and dining room were designed to meet the normal heat losses of the rooms and so were incapable of the increased output necessary to maintain these rooms at design temperature when the doors were permanently open. Their heat output was therefore supplemented by thermostatically controlled low-temperature electric convectors placed immediately in front of the radiators.

5.2 Results

Two sets of experiments were undertaken. In the first, the rates of air change in the lounge and dining room were measured with both doors permanently open, for various combinations of door openings in the other parts of the house. In the second, measurements were made of the initial surge of room air upon opening the lounge door after it had been closed for a long period.

The results are summarised in Table VIII, together with the relevant room temperatures. It will be seen that very large quantities of air leave the downstairs rooms if the doors are left open permanently and that quite massive heat transfers can occur. Some idea of the order of magnitude of these flows may be obtained from Fig. 3, which refers to Test 2 in Table VIII. It will be seen that the air leaves the room at approximately 75°F and returns at a temperature between 58°F and 60°F. Similar figures were recorded for Test 1.

Test 1 was undertaken at the end of a long period of overcast skies when the outside temperature had remained constant for some thirty-six hours. Since the conditions prevailing during the test had been maintained for the whole of this period, it was most likely that a stable rate of heat loss from the house had been attained which would be very close to the steady state heat loss assumed in design calculations.

From the various known inside temperatures it was possible to calculate (*a*) the heat losses from the unheated parts of the house and (*b*) their heat gain, by conduction, from the heated rooms; the difference between these two calculated quantities represents the heat transferred by convection from the heated to the unheated rooms.

Checks had already shown that the air change rates for the lounge and dining room were very nearly equal, and it was assumed that the convection gain by the unheated rooms was derived in equal parts from these rooms. Thus, as the outgoing and return temperatures of the warmed air were known, it was possible to calculate the air flow necessary to provide the "convection gain". This was found to be 16 000 cu ft/h from each of the downstairs rooms, a figure which agrees well with the 16 500 measured for the lounge. In Tests 3 and 5 the outside temperature had again been sufficiently stable to assume steady state heat loss, so similar calculations were made in these two cases. The results are shown in Table VIII.

Although the calculated and measured air flows correspond remarkably well, too much weight should not be attached to this. Many factors are involved in the heat transfer calculations, and the close agreement with the actual flow is thought to be largely fortuitous. However, it can be taken that the calculated flows confirm the approximate magnitude of the measured flows, which, taken by themselves, are surprisingly high.

The results of Test 1 seem to indicate that adequate bedroom heating can be achieved by leaving the downstairs and upstairs doors open. However, this is only partially true. For instance, the results show that the heat transfer to the bedroom is sufficient to maintain a 20 deg. F inside-outside temperature difference. Thus a relatively small increase in outside temperature would cause the bedrooms to be overheated and, in fact, it is likely that as the outside temperature increased, the bedroom temperatures would tend to approach those of the downstairs rooms. Conversely, in very cold weather the bedrooms would probably be underheated.

Also, it must be remembered that the results for Test 1 were obtained with all the windows shut. The opening of one upstairs window (W.C.) materially affects the position as will be seen from Test 2. Here the flow from the lounge is somewhat greater than in the previous test, but the heat gain by the bedroom is only sufficient to maintain a 9 deg. F inside-outside temperature difference, which suggests that something like half of the heat previously supplied is being lost to outside. Indeed, comparison with Test 6, where the bedroom doors were shut and the outside temperature was similar, seems to indicate that the bedroom was receiving very little heat transfer by convection in Test 2.

Even if satisfactory bedroom heating were obtained by heating the downstairs rooms only, it would appear to result in most unsatisfactory conditions for the downstairs rooms. The temperatures in Fig. 3 are fairly typical of those prevailing throughout the tests when the bedroom and downstairs doors were permanently open, and it is apparent that there were very large temperature gradients between floor and head level—gradients that were, in general, nearly twice as large as those experienced when the doors were shut.

The flows in Tests 3 and 4 are less than in the other doors-permanently-open tests. This is to be expected, as the bedroom doors were shut so that the heat loss by the convection stream was reduced, and the cooling of the warmed air was correspondingly less; the flow could therefore be expected to be less vigorous than when the bedroom doors were open. The conditions of Tests 3 and 4 are very similar to those which would occur in an open-plan house in this country, where it is unusual for bedroom doors to be left open. The results show that, in these circumstances, bedroom heating is inadequate so that it is not possible to obtain whole-house heating by heating the downstairs rooms only. These two tests should be compared with Test 6 where the W.C. window and door were open. It will be seen that the opening of one small window causes a very large increase in flow.

The tests (7 and 8) in which the initial surge from the room was measured gave air flows very similar to those obtained when the lounge and dining room doors were permanently open. This is probably due to the fact that outside temperatures were higher when these measurements were made, with the consequence that the unheated parts of the house were almost as warm as they were during the doors-permanently-open tests. It will be appreciated that the flow from the heated room will largely be determined by the temperature difference between it and the rest of the house.

The fact that these large flows out of heated downstairs rooms occur when the door is opened means that the normal movements of the occupants about the house will permit appreciable heat transfers to take place. They explain the fact that the use of hall radiators is sometimes unnecessary, since this part of the house can be adequately heated by the intermittent heat spillage which occurs when downstairs rooms are opened.

To summarise, the results discussed in this section indicate the undesirability of keeping downstairs doors permanently open. In most circumstances, where the bedroom doors are shut, little or no heating of the bedrooms will occur and large heat losses are likely to result if a landing window is open. Even if the bedroom doors are open, large heat losses will still occur if an upstairs window is open, whereas overheating is likely if all the windows are shut.

6. AIR MOVEMENT WITH FORCED-CIRCULATION DUCTED WARM-AIR SYSTEMS

The previous section considered whole house heating by movements of warm air under natural convection. In the U.S.A. it is common to heat by forced-circulation ducted warm air, and recently interest has been shown in employing a similar principle in this country. Among the factors which make for efficiency in the American system are almost complete exclusion of air flow to outside the house (apart from a controlled amount of ducted ventilation) and large ducts with multiple inlet and outlet registers giving a high degree of recirculation. These conditions are easily obtained in American houses, where double glazing and storm sashes provide a high degree of airtightness, and where frame construction allows a complete system of flow and return ducts to be housed unobtrusively.

In this country traditional methods of building make the installation of any system of ducts difficult, particularly in existing houses, and it is thus common practice in all but the most expensive systems to provide only supply ducts to the rooms to be heated, omitting return ducting. The inlet to the circulating fan is situated either in the hall or in the upstairs landing space and it is claimed that the leakage around internal doors is sufficient to ensure reasonable recirculation of the warmed air. Only in relatively few cases are grilles provided in internal doors to assist recirculation.

Warm-air systems of this type are becoming increasingly common, and in view of the interest which is being shown in them it was decided to use the tracer technique to study the air movements they caused and, in particular, to investigate the amount of recirculation which occurred under various conditions.

A forced-circulation warm-air system was therefore installed in the house described in Section 2 and illustrated in Fig. 1. The system used was typical of many at present available and was based upon a prefabricated unit containing a fan-type impeller and heat exchanger. On the advice of the manufacturers this was mounted on the wall between the stairway well and room B_3 (see Fig. 1), with the inlet to the fan 15 in below the ceiling and the outlet connected with ducting to registers at skirting level in rooms L, D, B_1, B_2 and B_3. The cross-sectional areas of the various ducts were in accordance

Table VIII.—Air movements within the house, heating from downstairs rooms only.

Test No.	Conditions									Air Flow Rate (cu ft/h)	
	House				Temperatures (°F)			Wind			
	Doors open	Windows Open	Rooms Heated	Tracer Released in Room	Outside	L (Mean)	B_1 (Mean)	Speed (m.p.h.)	Direction	Measured	Calculated (Heat flow Btu/h)
Steady Conditions: Stated doors permanently open.											
1	L, D, $B_{1, 2, 3}$	None	L, D	L	36	67	56	15–22	ENE	16 500	16 000 (3215)
2	L, D, $B_{1, 2, 3}$, W.C.	W.C.	L, D	L	48	70	57	10–15	E	17 600	—
3	L, D	None	L, D	L	36	72	52	10–15	ENE	13 700	14 500 (2350)
4	L, D	None	L, D	L	40	71	53	10–15	ENE	13 700	—
5	L, D	None	L, D	D	36	66	51	10	NE	15 500	16 800 (2420)
6	L, D, W.C.	W.C.	L, D	L	44	70	56	6–10	NE	17 600	—
Initial Surge: Heater room to unheated house.											
7	None except L during test	None	L, D	L	45	70	56	6–10	NE	13 900	—
8	B_1 permanently + L during test	None	L, D	L	47	70	57	6–10	NE	16 000	—

with the maker's instructions and the warmed air (at 120°F) supplied to each of the rooms was sufficient to meet the design heat losses.

As has been explained in Section 5, the tracer technique cannot be used to measure the air change in a single room if recirculation of tracer-laden air is present. It was thus impossible to investigate the air change of individual rooms separately, when all were being supplied with tracer-laden air. Instead the whole house (excluding the bathroom, W.C. and kitchen) was treated as a single unit and sufficient Geiger tubes were used to enable the change in mean tracer concentration with time to be found, and hence the rate of air change for the whole space.

Earlier experiments had shown that the mean tracer concentration in each room could be measured by placing a Geiger tube approximately at the room centre. Two tubes were necessary for the hall and landing space; one midway between the front door and the staircase at about 5 ft 6 in above floor level, and one above the stair head about 5 ft above the landing.

Since all the rooms being supplied with warm air were to be treated as a single unit, it was essential to introduce tracer into each of them at the same time. The ducted warm-air system provided a means of doing this and the tracer was introduced into the fan inlet in sufficient quantities to give a workable count rate in each room. After allowing sufficient time to ensure adequate distribution and mixing of the tracer, the readings were taken from each of the Geiger tubes in turn, their output being switched successively to a high-speed recorder. A set of seven readings (one from each tube) took between 1·5 and 2·5 min to complete and in each test at least five such sets of readings were taken.

The count rate readings for each room were plotted against time and interpolations were made at fixed intervals. The values so obtained were multiplied by the room volume and the products summated to give a figure directly proportional to the weight of tracer remaining in the house for the whole space under examination. The values so obtained were plotted against time, and the rate of air change calculated in the manner described in Section 1.

Exploratory tests with a sensitive micromanometer showed that for wind speeds below 25 m.p.h. the hall was at a reduced pressure relative to the adjacent rooms (including those without ducts) and to the air outside the house. Thus the only air movement out of the hall was through the circulating fan, and the measured air change was taking place solely from the rooms supplied with ducted warm air. The rate R_1 at which air was supplied by the fan was measured, the rate of recirculation being the difference between this and the rate of air change R_2.

Using this technique, a range of conditions was examined embracing the extremes of normal operation. For each arrangement of door and window openings, tests were undertaken to assess the air change with and without the fan running. When the fan was off the conditions in the house were very similar to those obtained with conventional central heating. The "fan-off" figures may therefore be taken as a basis for comparing the air changes normally encountered with conventional systems with those caused by warm-air systems of the type under consideration.

The range of conditions tested are set out in Table IX. It will be seen that two main sets of tests were carried out and in each the effect of opening doors and windows was examined. In the first the flues in the room were completely sealed but in the second they were left open, giving an opening into the chimney similar to that which would be obtained with a simple open fireplace.

It may be argued that this latter set of conditions is not normally encountered in practice, but unfortunately this is not true. Many such systems are installed in houses, where the existing flues are not always sealed. In fact, at least two large building companies are at present installing forced-circulation warm-air systems in new houses with open fireplaces in the downstairs rooms and in one case the discharge register is situated in the vertical face of a raised hearth of an open fireplace.

From the table it will be seen that the best recirculation (about 80 per cent.) was obtained with all the internal doors open, and with the windows shut, the ventilation loss being approximately the same as that when the fan was off. Operating the system in this manner minimises the ventilation loss, but leads to undesirable thermal conditions, since the temperatures throughout the house tend to equalise, resulting in overheating of the hall, upper landing and bedrooms.

When the transom windows and doors are all open the recirculation is much less, being about 50 per cent. In this state, moreover, the ventilation losses are high when the fan is not running. This is in line with the findings described in the previous section and increases the doubts expressed there about the practicability of heating "open-plan" type houses.

When the internal doors are shut the recirculation is also poor; with the windows shut some 40 per cent. of the warm air is lost, and with them open about 60 per cent. In both cases shutting off the fan causes a large decrease in ventilation losses.

With the chimneys unsealed the ventilation losses are considerably increased; this is to be expected, as the chimney opens up an additional low-resistance path to atmosphere. It should be noted that the present series of tests were undertaken in conditions of almost complete calm, and this probably explains the relatively low chimney flows, which were measured with the fan off. Under the more normal wind conditions in which the tests in single rooms were undertaken (Section 4) considerably larger air changes were measured in the same rooms with their chimneys unsealed. The effect of an enhanced chimney pull due to wind action, however, would also affect the tests with the fan on, and it is probable that the recirculations quoted are, therefore, as high as any which would normally be experienced.

The experiments so far discussed have been concerned with whole-house heating. However, one of the advantages claimed for warm-air systems is that the heating can be concentrated in any desired room by closing the outlet registers in the other rooms. It was decided, therefore, to investigate the operation of the system when only one room was being heated, the supply to the other rooms being shut off. Three rooms were used for these tests, namely the lounge (L) and the two main bedrooms (B_1 and B_2). Tracer was released in the room under test and the mean concentration both in it and the hall and landing space monitored.

Three methods could be used to calculate the results.

Table IX.—Rates of air change (whole house)—Forced-circulation ducted warm-air Heating Systems.

Flues	Windows	Internal Doors	Fan	Test No.	Rate of Air Change (cu ft/h) R_2	Fan Output (cu ft/h) R_1	Per cent. Recirculation
Sealed	Closed	Closed	Off	1	5 050	—	—
			On	2	11 300	29 150	61·2
		Open	Off	3	6 050	—	—
			On	4	6 350	31 200	79·7
	Transoms open (40 sq in in each room, 60 sq in on landing)	Closed	Off	5	11 700	—	—
			On	6	18 200	30 500	40·7
		Open	Off	7	16 600	—	—
			On	8	15 600	31 700	50·8
Open	Closed	Closed	Off	9	6 800	—	—
			On	10	25 900	33 250	22·2
		Open	Off	11	6 350	—	—
			On	12	16 150	34 450	53·2
	Transoms open (40 sq in in each room, 60 sq in on landing)	Closed	Off	13	11 200	—	—
			On	14	33 800	35 900	5·8
		Open	Off	15	10 850	—	—
			On	16	26 150	35 000	25·3

The first was that already described for the whole-house tests. This method involves a relatively large amount of tedious calculation and an examination of the problem showed that, where only one room and the hall-landing space are involved, the methods described in the Appendix could be used with a considerable saving in time. For the first three single-room tests the results were calculated by all three methods and good agreements were obtained. Subsequently the first of the methods described in the Appendix was used.

The results of these tests are summarised in Table X, from which it will be seen that there are a number of differences from the whole-house tests. First, concentrating the supply to a single room considerably increased the input of warm air. The lounge normally received about 10 000 cu ft/h, but with the supply to the other rooms shut off this increased to between 15 000 and 17 000 cu ft/h. Thus the actual air loss for the same percentage recirculation is considerably greater.

Table X.—Rates of air change (single rooms)—Forced-circulation ducted warm-air heating system flues sealed. Air supply to stated room only.

Room	Window	Door	Rate of Air Change (cu ft/h)	Fan Output (cu ft/h)	Per cent. Recirculation
L	Closed	Closed	10 450	15 750	33·6
		Open	2 950	17 900	83·4
	Open (40 sq in)	Closed	12 850	16 700	23·2
		Open	5 650	18 150	68·8
B_2	Closed	Closed	3 100	4 650	33·2
	Open (40 sq in)	Closed	4 180	4 650	10·0
B_1	Closed	Closed	3 380	5 100	33·7
	Open (40 sq in)	Closed	3 980	5 150	22·8

In addition, the percentage recirculation with the room door closed is generally lower than the average for the whole-house tests. This is probably a consequence of the change of pressure distribution in the house brought about by closing all but one register. With air being supplied to all the rooms, leakage from them takes place to outside. When, however, all but one are receiving no air supply these are at a slightly reduced pressure relative to outside, the leakage is inward and new leakage paths to the inlet of the fan are created.

In addition, since the room being supplied with warm air receives a considerably greater supply than when all the other registers are open, its pressure relative to outside the house is increased. On the other hand, the hall pressure is relatively higher than when all the registers are open (although still less than that outside the house), as the fan is extracting less air from the hall and landing space. The result of these two effects is that the pressure drop across the windows increases to a greater extent than that across the door: in consequence the leakage to outside increases by more than the recirculation around the door.

The effect of the reduced percentage recirculation (shown in Table X), coupled with the enhanced air supply, is that the air loss from the lounge is considerable and with the door shut is of the same order, or somewhat larger, than that so rightly condemned when caused by the simple open fire.

To summarise this section it is true to say that the results cast considerable doubts upon the efficiency of systems of the type examined. Reasonable recirculation and low ventilation losses can only be obtained by dispensing with doors on all the rooms supplied with warm air and keeping windows shut. Neither of these arrangements is in accord with traditional British habits, and even the so-called "open-plan" houses retain bedroom doors which are normally kept shut during occupancy.

However, even if complete open-plan arrangements were adopted it is dubious whether any great advantage would accrue. True the ventilation losses would be considerably reduced (provided always that windows were not open), but it would be impossible to avoid a large degree of temperature equalisation over the house, which would result in bedrooms, hall and landing space being overheated. Conduction heat losses would then be large and probably sufficient to offset any gain due to the better recirculation.

With forced-air systems of the type used the bedrooms present another problem. It is probably undesirable to heat them during the day-time if economy of operation is to be achieved. If, however, the inlet registers of the bedrooms are closed there is a marked tendency, particularly when the living rooms' doors are shut, for the ventilation losses in the living rooms to be made up by air drawn to the fan inlet through the bedrooms, thus, of course, cooling them. The user would therefore appear to have little choice between needlessly heating unoccupied rooms, and cooling them.

The various difficulties discussed above are almost entirely the result of dispensing with return ducting from the heated rooms which suggests that, when using warm-air heating, it is imperative to follow American (and best British) practice and provide both flow and return ducting.

7. CONCLUSIONS

The lessons to be drawn from each set of experiments have, in general, been discussed on examining the results. Certain of them are, however, important enough to bear reiteration.

First, the experiments have provided further evidence of the excessive and wasteful ventilation caused by the ordinary open fire, and the disadvantages of using this type of appliance in centrally heated houses, or indeed leaving it in position with its flue unsealed, have been shown. If an open fuel bed is required to form a focal

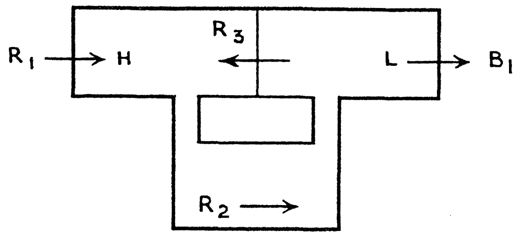

Fig. 4.

It is necessary to assume that there is instantaneous mixing of the tracer at all times in each room L and H.

If the volumes of the rooms are V_L and V_H then, since the method involves a measure of the concentrations of tracer present, the change (dx) in Geiger tube count rate (x) in the same time interval dt is given by

$$kV_L\frac{dx_L}{dt} = k(R_2x_H - R_1x_L - R_3x_L) \quad .. \quad (3)$$

$$kV_H\frac{dx_H}{dt} = k(R_3x_L - R_2x_H) \quad .. \quad .. \quad (4)$$

where k is a constant.

Hence from equation (4)

$$V_H\frac{dx_H}{dt} = R_3x_L - R_2x_H \quad .. \quad .. \quad (5)$$

and when $dx_H/dt = 0$, i.e. when the concentration of tracer in H has reached its maximum value

$$R_3 : R_2 = x_H : x_L \quad .. \quad .. \quad (6)$$

Hence the per cent. recirculation (100 R_3/R_2) is given by $100x_H/x_L$.

However, it is possible to evaluate this by another method, for from the equations (3) and (4)

$$V_L\frac{dx_L}{dt} + R_1x_L = - V_H\frac{dx_H}{dt}$$

hence when $dx_H/dt = 0$

$$R_1 = - V_L\frac{1}{x_L}\cdot\frac{dx_L}{dt}$$

Thus by taking the tangent to the curve of tracer concentration in L at that value of t corresponding to $dx_H/dt = 0$, it is possible to evaluate R_1 numerically. Thus, knowing R_2, it is also possible to calculate R_3 and hence the recirculation.

point in a centrally heated room, it should be provided by a freestanding convector open fire with a restricted throat. An appliance of this type will limit the ventilation to a reasonable level when it is alight, and, providing the throat restrictor is set at its minimum opening, prevent excessive ventilation when it is not in use. In the rooms which were centrally heated by hot water radiators, air changes slightly below those allowed for in conventional design calculations occur. By opening windows the ventilation rates can be increased to around the figure normally taken for design, and it is thus generally true to say that the design figure is a realistic one. Misuse of windows and the consequently high ventilation rates which may occur cannot, of course, be allowed for in any design procedure.

If internal doors are left open, very large rates of air change occur. This air movement takes the form of convection flow to the upper storeys and carries with it significant amounts of heat, which are sufficient, if all the bedroom doors are kept permanently open and all the upstairs windows are shut, to overheat the bedrooms. If, on the other hand, only one small window is open in an upstairs room with an open door, significant wastage of heat occurs.

Although large heat transfers to the upstairs rooms may occur when the downstairs and bedroom doors are left open, the heating of the bedrooms is insufficient if their doors are shut and, in these circumstances, the hall and landing only are heated. Thus, in this country, where it is common practice to keep bedroom doors closed, there would appear to be little prospect of success for systems based on heating only the downstairs rooms in a so-called open-plan house.

Forced-circulation ducted warm-air systems without a return duct from each room are shown to have serious failings. Very large heat losses occur if the door of the room into which the warm air are discharged is closed. Even with the room door open, satisfactory circulation is not always achieved, and moreover such an arrangement leads to undesirable temperature distribution which may considerably increase the conduction heat losses by causing overheating in the bedrooms.

Finally, the radioactive tracer technique showed considerable sensitivity and flexibility in dealing with these problems. Perhaps its most important advantage over the older chemical tracer method is the very rapid response of the detectors, which enable quickly changing conditions to be investigated. It seems unlikely that either the experiments on the air movements from a room with its door open, or those on the ducted warm-air systems, could have been undertaken by any of the existing chemical tracer techniques.

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APPENDIX

Method of Evaluating the Recirculation of Air from a Room in a House with a Ducted Warm-Air Heating System

Consider a room L connected to the hall H of the house by a doorway. With a ducted system as shown (where air is being passed through the heating system from H to L at a rate R_2), the pressure differences will be such that there will be a loss of air from room L both through the windows at a rate R_1, and by recirculation to H at a rate R_3. (The flue in room L is assumed to be sealed.)

For similar reasons there will be a net gain of air by the Hall from all other rooms and from the outside, also at a rate R_1.

If a tracer is released in room L, then at any time t, in a time interval dt the change in total weight (dw) of tracer in each room L and H will be

$$\mathrm{d}w_{\mathrm{L}} = R_2 \,.\, \mathrm{d}t \,.\, c_{\mathrm{H}} - R_1 \,.\, \mathrm{d}t \,.\, c_{\mathrm{L}} - R_3 \,.\, \mathrm{d}t \,.\, c_{\mathrm{L}} \,.. \quad (1)$$

$$\mathrm{d}w_{\mathrm{H}} = R_3 \,.\, \mathrm{d}t \,.\, c_{\mathrm{L}} - R_2 \,.\, \mathrm{d}t \,.\, c_{\mathrm{H}} + R_1 \,.\, \mathrm{d}t \,.\, (0) \quad (2)$$

where c_{L} and c_{H} are the concentrations of tracer in each room at time t.