VENTILATION IN RELATION TO TOXIC AND FLAMMABLE GASES IN BUILDINGS

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Reprinted from: Building Science, Vol 8, 1973, pp 289-310

The toxic and flammable gases and vapours that lead to hazards in buildings are discussed. The trends in accidental deaths in the home in England and Wales from gas poisoning are examined: the number of deaths per annum from town gas have fallen dramatically from the peak in 1963 of 1230 to less than 200 in recent years, but the number due to carbon monoxide from heating appliances has steadily increased from about 10 in the early 1950s to about 70 in recent years.

The influence of buoyancy on the dilution by ventilating air of accidental leaks of toxic and flammable gas is discussed and the limiting cases, where buoyancy effects are negligible and where they dominate, are theoretically investigated. The variation of contaminant concentration with time is derived for situations where buoyancy has a negligible effect on the mixing process and it is shown by experiments in a mechanically ventilated office that turbulent mixing with the room air can extend to the corners of the room, above cupboards and below tables.

Where buoyancy dominates layers can readily form; this is important when considering explosion hazards. The concentration distribution in roof layers for ventilation systems extracting air through an outlet near to, but not in, the roof is calculated theoretically. The theory assumes that the mixing of the gas with the ventilating air takes place by molecular diffusion and is shown by the comparison with experiment to apply in practical situations.

It is shown theoretically that a leak of town gas near to the floor mixes readily with the room air during its flow towards the roof. Simple experiments using nitrous oxide demonstrated the relevance of the theoretical approach to conditions that can arise in buildings. The combination of ready mixing of a buoyant plume during its vertical motion and subsequent mixing only by molecular diffusion once a layer has formed against the roof explains how a gas accumulation may have led to the explosion at Ronan Point.

Theoretical results are tabulated and presented on design charts for controlling gas hazards in buildings by ventilation for a wide range of practical situations.

Attention is drawn to possible future hazards from gas accumulations in the space above false ceilings and in near horizontal common service ducts and tunnels.

A new technique is suggested for measuring ventilation, mainly for mechanically ventilated buildings when there is appreciable adventitious ventilation. This uses a steady release of tracer gas and enables both the mechanical ventilation output rate and the adventitious input rate to be determined from a single series of measurements. These cannot be separated in the usual tracer gas dilution technique.

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Ventilation in Relation to Toxic and Flammable Gases in Buildings

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INTRODUCTION

THERE are two main hazards from gases in buildings, explosions and poisoning. Poisoning leads to the greatest number of lives lost per year. Explosions, however, can be spectacular, e.g. the progressive collapse of the flats at Ronan Point in May 1968, although this was not as violent as the explosion in Glasgow in October 1971 which killed 20 people. A large number of common substances can, if the conditions are right, lead to explosions. Gas poisoning in buildings is almost always due to one substance, carbon monoxide. There are two main sources of carbon monoxide; town gas (utility gas) is at the present time the most common source of incidents leading to death but leaks of carbon monoxide produced by incomplete combustion in heating appliances represent an increasing cause of gas poisoning.

The present paper gives details of the flammable gases and vapours which may be found in buildings, considers the control of accidental leaks of toxic and flammable gases by ventilation, their detection, and finally looks to the future for unusual gas hazards which may occur.

Gas poisoning in the home

The number of accidental deaths in the home arising from various causes are collected and published by the General Register Office [1]. By looking at the deaths over a long period it is possible to smooth out the fluctuations, probably due in part to extreme weather conditions, and to determine trends. Figure 1 shows the number of deaths per year from utility gas plotted over the period 1950–1970 for England and Wales. The numbers of deaths are shown for three age groups: the 'under 65s', '65 and over' and the total for 'all ages'. It can be seen that there are clear trends for each age group; the curves show an increase from 1950, which had a total number of deaths of about 390, rising to a peak in 1962/3, of about 1230. From 1963 onwards a rapid decrease takes place with the number in 1969 having fallen to about 290. About three-quarters of the deaths are in the age group 65 and over. The deaths are mainly caused by the highly toxic component of town gas, carbon monoxide, which can lead to death in concentrations less than 0·1 per cent. Up until about 1960 virtually all utility gas was made from coal with the result that the proportion of carbon monoxide in the gas was high, about 15 per cent. From about 1960 an increasing proportion of gas was prepared from oil and consequently smaller carbon monoxide concentrations reached some consumers. In recent years methane, first from Algeria and now increasingly from the North Sea, has formed a significant proportion of the utility gas and where these are the sole sources the carbon monoxide concentration is virtually zero. The rise in the number of deaths over the 1950s coincided with the rise in the use of utility gas in the home and the fall in the 1960s is probably due to the decreasing toxicity of the gas supplied.

North Sea gas is virtually non-toxic and the only hazard from breathing it occurs when the concentration is so high that there is insufficient oxygen in the gas–air mixture for life to be supported. This occurs at concentrations of more than about 30 per cent, an order of magnitude greater than for poisoning by utility gas prepared from coal.

The next important category of gas poisoning in the home is carbon monoxide from other sources, designated in the Annual Abstract of Statistics as "other carbon monoxide gas". This refers to carbon monoxide released from sources other than town gas, principally leaking combustion gases from many types of heating appliance. The number of deaths per year over the period 1950–1969 is shown in figure 2. The number of deaths per year is much smaller than that due to town gas but it does show a steady increase, rising from about 10 per annum in the early 1950s to about 60 per annum in the late 1960s.

The fact that the number of deaths has increased so much over the 20 year period may partly be due to the increase in the number of central heating appliances fitted into old homes and partly to the tendency towards poor ventilation in homes in general due to the sealing up of disused flues associated with open fires and the "draught proofing" of windows.

Carbon dioxide

As far as the authors are aware there have been no reported cases of accidental death arising from the presence of carbon dioxide (CO_2) in the home. This is a product of combustion as is carbon monoxide and can lead to death in concentrations below those required for asphyxiation. There is no clearly established level at which the carbon dioxide is dangerous but at concentrations above about 5 per cent judgement becomes impaired and at concentrations above 10 per cent death will occur.

When a building catches fire deaths may be caused by the carbon monoxide from combustion.

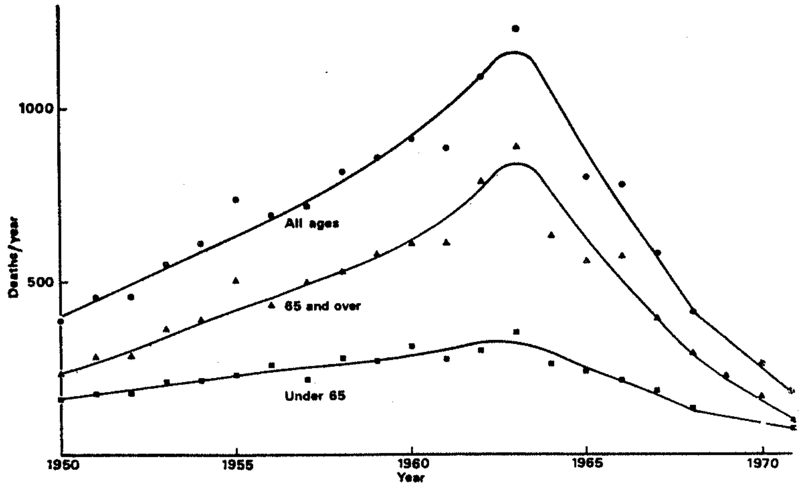

Fig. 1. Number of deaths per year for accidental poisoning by town gas in the home.

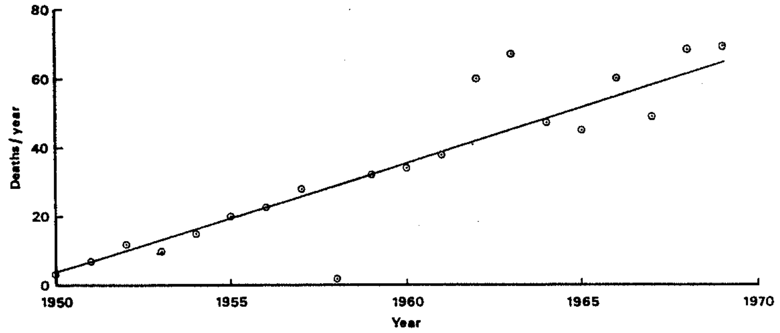

Fig. 2. Number of deaths per year for accidental poisoning in the home by carbon monoxide from sources other than town gas.

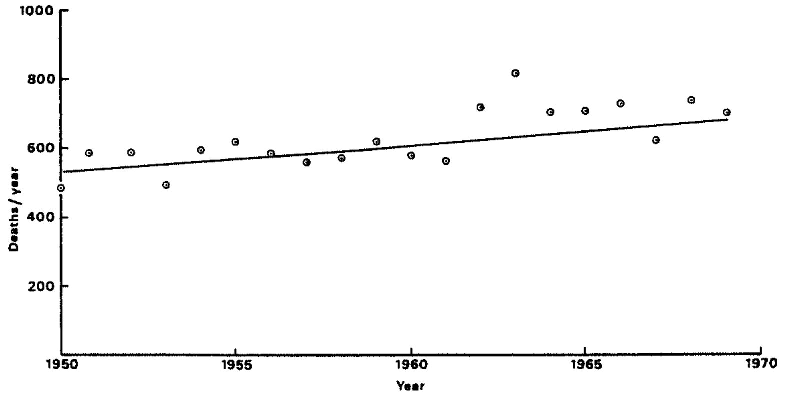

Fig. 3. Number of deaths per year from fire and explosion in the home.

However, deaths arising from this have been excluded from the category of poisoning by carbon monoxide and are classified in the Annual Abstract of Statistics under Death by Fire and Explosion. Total deaths from fire and explosion are shown in figure 3 over the same period as before. A steady increase in the annual number of deaths can be seen rising from 550 in the early 1950s to about 700 in the late 1960s.

Explosions

Daxon and Fry [2] reported that in the 10 year period, 1960–69, 24 deaths occurred from town gas explosions and five from liquified petroleum gas explosions.

An estimate of the number of explosions in domestic premises was given in the report of the inquiry into the collapse of flats at Ronan Point [3] and Table 1 is taken from that report. The estimates were made by sampling reports made by Fire Brigades over the period 1957–1966. The number of explosions per year averaged about 190 without any discernible trends. About 75 explosions each year were due to town gas, 10 due to liquified petroleum gases, 30 due to flammable liquids and a further 75 from other and unknown causes. It can be seen from the table that the number of explosions classed as superficial was about a half of the total, the remainder involving structural damage.

Chambers [4] looked at the material damage and injuries due to gas explosions in dwellings in 1969.

Table 1. Frequencies of explosions in domestic premises estimated from samples of fire brigade reports—damage and explosive material

Year	Sampling factor	Total explosive	Town gas			Liquefied petroleum gases			Liquids			Other and unknown
			Total	Super.	Struc.	Total	Super.	Struc.	Total	Super.	Struc.	
1966	1/1	213	97	55	42	14	8	6	33	25	8	69
65	1/1	181	76	40	36	14	8	6	29	20	9	62
64	1/2	168	80	28	52	8	—	8	18	16	2	62
63	1/6	216	84	54	30	6	—	6	18	12	6	108
62	1/2	234	70	20	50	8	2	6	34	28	6	122
61	1/2	198	46	28	18	10	4	6	38	30	8	104
60	1/4	144	72	36	36	16	—	16	12	8	4	44
59	1/4	148	88	24	64	—	—	—	24	20	4	36
58	1/4	192	64	28	36	12	—	12	48	32	16	68
57	1/1	195	70	41	29	8	3	5	44	35	9	73
Total	—	1889	747	354	393	96	25	71	298	226	72	748

The paper shows that with a total of 155 explosions due to town and natural gas in England, Wales and Scotland there were 44 people injured; 1 explosion where the material damage was valued at over £10,000, 6 explosions where the damage was valued between £3000 and £10,000 and 10 explosions valued between £1000 and £3000. The paper divided the explosions between those due to town gas and those due to natural gas and suggests that the material damage arising from the natural gas explosions was similar to that arising from the town gas explosions, but the number of reports available on natural gas incidents was too small for the conclusion to be certain.

The most studied explosion was that which occurred in the flats at Ronan Point on 16 May 1968. A photograph of the damage is shown in figure 4. The inquiry into it concluded that the explosion was caused by town gas and that it was an explosion within normal limits in the sense that explosions of this magnitude must be expected from time to time in domestic buildings in which gas is used as a fuel. The unusual feature about the Ronan Point incident was that the explosion in one flat removed a structural supporting wall and caused a progressive collapse of flats above and below the one damaged by the explosion. Since this explosion took place there has been an amendment to the Building Regulations (1970) [5] intended to reduce the risk of progressive collapse in tall structures.

Discussions of hazards

In order to put the figures given above into perspective it is useful to consider their magnitude in relation to other causes of accidental death. The number of people killed on the roads is approximately equal to the number of people killed by accidents in dwellings, each totalling about 7000 per annum. At its peak the number of deaths due to gas poisoning, about 1250 in 1962/3, was a very large proportion of the number of accidental deaths. Today the situation is that the number of deaths due to town gas poisoning is decreasing, the number of deaths due to flue gas poisoning is increasing and the trend in the number of deaths due to explosion is uncertain but the total number is small.

Fig. 4. Damage at Ronan Point.

PROPERTIES OF COMMON TOXIC AND FLAMMABLE GAS AND VAPOURS

The important properties of common substances which can lead to explosions or to poisoning are shown in Table 2. This gives the toxic concentration, where applicable. Other substances can lead to asphyxiation in concentrations greater than about 30 per cent. Explosive gases and vapours have a range of concentrations over which combustion is possible. If a space is completely filled with flammable gas above the upper limit then that gas cannot take part in an explosion. Usually gas above the upper flammable limit will take part in

Table 2. Properties of common toxic and flammable gases and vapours

	Toxic concentration (%)	Limits of flammability (%)
Carbon Monoxide	~0·1†	12–75
Carbon Dioxide	~5	Non flammable
"Utility" or "Town" gas (Coal based)		5·5–31·0
Methane (Natural gas)	Non toxic*	5–15
Propane	Non toxic*	2·0–9·5
Butane	Non toxic*	1·5–8·5
Acetylene	Non toxic*	2·5–82·0
Hydrogen	Non toxic*	4–74
Petrol	0·10–0·15	1·4–7·6

*Noticeable symptoms of anoxemia in concentrations greater than about 33%.
†For an exposure of duration 1 hr.

an explosion because mixing will take place with air due to the flows which are set up during the progress of the explosion. It is therefore reasonable to consider in most practical situations that all gas above the lower flammable limit represents a hazard.

If we look at the table we can see that carbon monoxide is the most hazardous substance commonly found. It is toxic in extremely low concentrations, it can also enter into combustion and lead to explosions, with wide flammable limits.

Hydrogen is clearly a dangerous substance, it is liable to be present wherever lead–acid accumulators are used as it is released on charging, it is flammable over an extremely wide range and concentrations as low as 4 per cent can lead to explosions.

The most widely used substance in the future will, of course, be methane, or natural gas. This has flammable limits 5–15 per cent. It is non-toxic but like all gaseous substances (except oxygen) can lead to asphyxiation in concentrations greater than about 30 per cent.

VENTILATION

By providing ventilation to reduce the concentrations to below the lowest hazardous limit associated with the toxic or flammable gas or vapour it is possible to render any substance harmless. At first sight it would seem quite small ventilation flow rates are sufficient because, if we take methane as an example, it is only necessary to supply fresh air at 20 times the leakage rate to bring it below the lower flammable limit and render it harmless. This might be described as an absolute minimum ventilation requirement when considering the control of gas vapour hazards by ventilation. For this to apply it is clearly necessary for the fresh air entering the room and the gas or vapour leaking into the room to be completely mixed together near to the point of release. The air in a room is rarely at rest, several mechanisms exist which ensure that the air is constantly stirred into random turbulent motion; the forces acting arise from the wind, from temperature differences, giving rise to convection currents and, if mechanical ventilation is used, from a fan. Within the room stirring is induced by jets of air from fans, ventilators and cracks in windows and doors. It seems, therefore, reasonable to assume in many situations that a contaminating gas becomes readily diluted by the air in the room. However, where the buoyancy of the contaminating gas or vapour is important it may be unreasonable to make this assumption. In this case there is a tendency for the gas or vapour to stratify—forming a roof layer if the gas or vapour is lighter than the air, or a floor layer if it is heavier. Once stratification occurs there is a resistance to mixing because work has to be carried out against the force of gravity in order to break up the stratification. In many situations this means that a stable, stratified layer will be formed.

It is not possible to consider theoretically the complex mixing processes that take place in all conceivable practical situations. However, useful progress can be made by considering limiting cases. In many practical situations conditions will be close enough to these limiting ones for theoretical calculations to describe what happens in practice. The following cases are considered:

(1) The hazardous gas or vapour is readily mixed with the air in the room and this in turn mixes readily with any fresh air entering the room.

(2) The stratified situation in which there is no turbulent mixing taking place and diffusion of the gas occurs only by molecular motion, with a ventilation extract at a fixed distance from the roof.

(3) The rise and turbulent mixing of a leak of light gas as it proceeds to the roof and its further diffusion and mixing as it then spreads through the room space.

In each case progress was made by making a major assumption which made theoretical development possible and then carrying out experiments to compare with the theoretical results and show that the theory could be applied usefully to situations of practical interest.

THE DILUTION OF NON-BUOYANT GASES AND VAPOURS

If there is no density difference between the air in the room and the contaminant gas or vapour then mixing will readily take place by one or more of the mechanisms described above. Mixing is also rapid even where there is a density difference if the air is mixed by a fan or by convection energetically enough to overcome gravitational effects. Let us assume the contaminating gas is mixed with the air in the room in a time much smaller than that required for the mean concentration to significantly change, this can be thought of as "instantaneous mixing". We shall now apply this assumption to a range of situations and calculate the resulting gas concentrations.

Sealed room

The situation where gas is emitted at a volumetric flow rate V of concentration c_o* into a room of volume M without an entry of fresh air is illustrated diagrammatically in figure 5. If the concentration at time t is c,

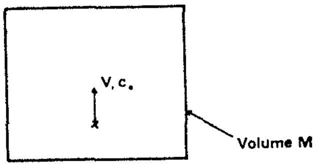

Fig. 5. Gas of concentration c_0 *produced in a room of volume* M *at a rate* V.

$$M\,\delta c = V c_o\,\delta t$$

$$\therefore\ \delta c/\delta t = V c_o/M$$

which can be integrated using the condition

$$c = 0 \text{ at } t = 0$$

to give

$$c = V c_o t/M \qquad (1)$$

Thus the concentration increases linearly with increasing time and the time required to produce a concentration c is given by

$$t = \frac{Mc}{Vc_o} \qquad (2)$$

The case considered here corresponds, for example, to a flueless convector heater burning at a constant rate in an unventilated but well stirred room. If the rate of production of carbon monoxide or carbon dioxide (or water vapour) produced by the heater is known then it is possible to calculate their concentration at time t from equation (1). At large times the heater will no longer produce the contaminant at a constant rate as the oxygen available for combustion will be significantly reduced because no fresh air replacement is taking place and furthermore the room pressure will rise due to combustion products. The equation cannot therefore be used to calculate more than the early stages of the build-up of the contaminant.

Room with an outlet but no fresh air inlet

Figure 6 shows a room into which contaminant enters but now an outflow of the room gas–air mixture can take place without an inflow of fresh air. In this situation

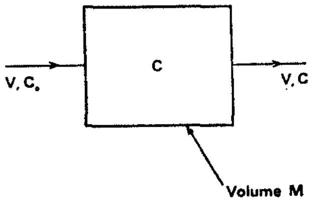

Fig. 6. Gas of concentration c_0 *entering a room of volume* M *at a rate* V. *Pressure build-up avoided by gas–air mixture leaving at concentration* c, *rate* V.

$$M\,\delta c = (V c_o - Vc)\,\delta t$$

which can be integrated using the condition that $c = 0$ at $t = 0$ to give

$$c = c_o(1 - e^{-Vt/M}) \qquad (3)$$

The increase of concentration with time is now exponential, the concentration in the room becoming equal to the input concentration at $t = \infty$. The time required to produce a concentration c is given by

$$t = -\frac{M}{V}\log_e\left(1 - \frac{c}{c_o}\right) \qquad (4)$$

It is convenient to discuss the application of equations (3) and (4) along with the situation considered next since these formulae are limiting cases of the more complex situation yet to be discussed.

Room with an outlet and a feed of fresh air

Although both the situations previously considered can occur in practice as limiting cases, a much more common situation is that shown in figure 7 where the room now has a supply of fresh

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*Concentration will be expressed as fractions by volume; to get the percentage concentration multiply by 100.

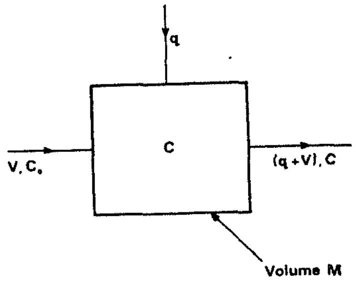


Fig. 7. Gas of concentration c₀ *entering a room of volume* M *at a rate* V *with fresh air ventilation* q.

air at a flow rate q. In this situation we get

$$M\,\delta c = [V c_0 - (q+V)c]\,\delta t$$

which can be integrated using the condition that $c = 0$ at $t = 0$ to give

$$c = \frac{c_0 V}{(q+V)}[1 - \exp\{-(q+V)t/M\}] \qquad (5)$$

Once again the increase of concentration with time is exponential but now the final concentration as $t \to \infty$ is no longer equal to the input concentration but is given by

$$c_\infty = c_0 V/(q+V)$$

and since q is likely to be much greater than V for most practical situations of interest this can be further simplified to give

$$c_\infty = c_0 V/q \qquad (6)$$

This expression is important since the ventilation requirement for controlling the hazard can be deduced from it. If the acceptable value of c_∞ is known then the required minimum ventilation is:

$$q = c_0\, V/c_\infty \qquad (7)$$

which can easily be calculated given the maximum credible gas leak which it is desired to control. Let us take an example—for a leak of methane, ideally we should want to keep the maximum concentration below the lower flammable limit of 5 per cent. The maximum leak may be taken as the flow rate resulting from severing a pipe e.g. 2 l/sec. This leak would be of natural gas containing 95 per cent methane so $c_0 = 0{\cdot}95$. The minimum ventilation rate required is therefore

$$\frac{0{\cdot}95 \times 2}{0{\cdot}05} = 38 \text{ l/sec}$$

On some occasions it may be necessary to know the time required to produce a given concentration or the concentration at a given time; these can be deduced from figure 8 in which concentration in the room c/c_0 is plotted against time in dimensionless form Vt/M, for different values of q/V. Figure 8 describes the build-up of a contaminant for a very wide range of ventilated and unventilated situations through its use of dimensionless co-ordinates.

The use of figure 8 can be illustrated by an example. Since the co-ordinates are dimensionless any self-consistent set of units may be used. If the contaminating gas is introduced at a volumetric rate of 1/100 of the room volume/hr and the fresh air ventilation is 1 room volume/hr, $q/V = 100$ and the gas concentration after 2 hr (when $Vt/M = 0{\cdot}02$) is given by $c/c_0 = 0{\cdot}086$ and hence $c = 8{\cdot}6$ per cent.

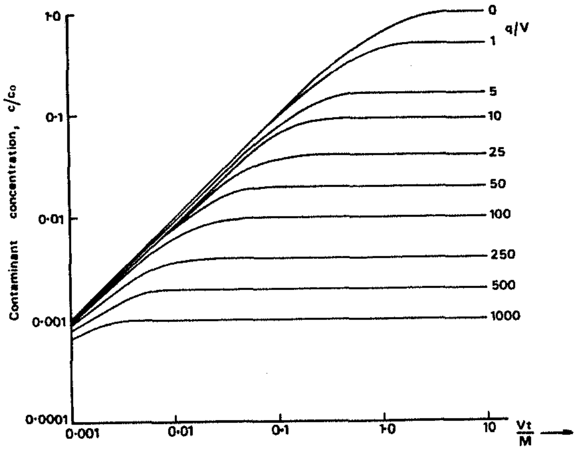


Fig. 8. Variation of gas concentration, c, *with,* t, *and ventilation rate,* q, *for gas leakage rate* V.

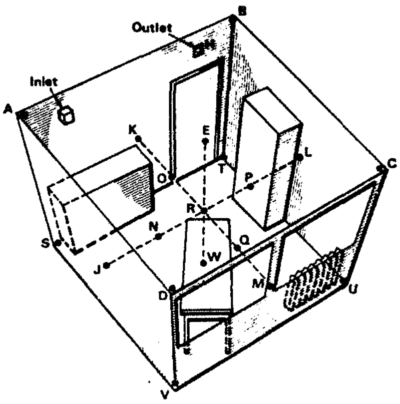
RV/H

It is common practice in ventilation engineering to use the expression ACH. This stands for air changes per hour and means that ventilation is provided equal to that number of room volumes per hour. The expression air changes per hour could be misleading to the non-ventilation engineer, since the air in the room is not in fact changed at that number of times per hour. The incoming air mixes intimately, for most ventilation arrangements, with the air already in the room, and the change of the air in the room for fresh air takes place exponentially in accordance with figure 8. Since the term ACH therefore gives a misleading description of the behaviour of the ventilating air the authors propose the expression *RV/H* which stands for room volumes per hour.

Experiment illustrating rapid mixing

An experiment was carried out to demonstrate that in some circumstances the assumption of instantaneous mixing of the incoming air is valid for all parts of a room—even in corners, under tables etc.

The room used was an office in a building with a plenum heating and ventilation system which fed fresh heated air into the room through a grill and withdrew air through a second grill. For experimental purposes, the incoming air was "marked" by adding to it a known proportion of a tracer gas (carbon dioxide). As the air in the room at the start of each experiment was gradually replaced by fresh "marked" air, there was a corresponding build-up of carbon dioxide; a record of the progressive replacement of air could thus be obtained from measurements of the variation of carbon dioxide concentration with time.



SAMPLING POINTS
Each corner and centre of ceiling A, B, C, D, E.
Against outlet _ _ _ H.
Centre of each wall _ _ _ J, K, L, M.
Centre of room _ _ _ N, O, P, Q, R.
Each corner and centre of floor _ S, T, U, V, W.

Each letter indicates the position of one of the 2mm internal diameter tubes used for extracting carbon dioxide samples. The carbon dioxide supply system is shown in fig.10

Fig. 9. *Measurement positions for experiments on room ventilation.*

The office used for the experiments and its furniture are shown in figure 9 which also gives the points at which the carbon dioxide concentration was measured. It was a room 4×3 m, approximately $2\frac{1}{2}$ m high. The ventilation inlet and outlet grills were located in one wall and the wall opposite contained two $2 \times 1\frac{1}{2}$ m windows with a hot water radiator below one of them. The radiator provided heat to counterbalance the fabric losses of the room, and remained on throughout the experiments. The windows were not openable, and the door was kept closed throughout each experiment. The temperatures of the inlet air, the room (centre) and the air outside the windows were 23°, 19° and −2°C respectively before and after the experiments.

A duct of length 0·15 m was attached to the air inlet grill as shown in figure 10 and carbon dioxide was fed into the duct at a steady rate through four pipes spaced equally around the duct. The carbon dioxide supply was arranged as shown in figure 10, heat being supplied in order to restore heat lost by evaporation and expansion to atmospheric pressure.

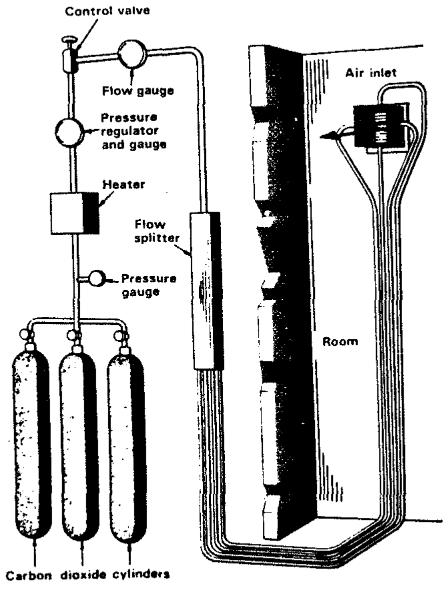


Fig. 10. *Carbon dioxide tracer gas supply system for experiments on room ventilation.*

The variation of carbon dioxide concentration with time was measured at the 20 points marked in figure 9 by withdrawing samples through narrow-bore tubes connected to a thermal conductivity analyser, which measured to an accuracy of about 0·2 per cent carbon dioxide.

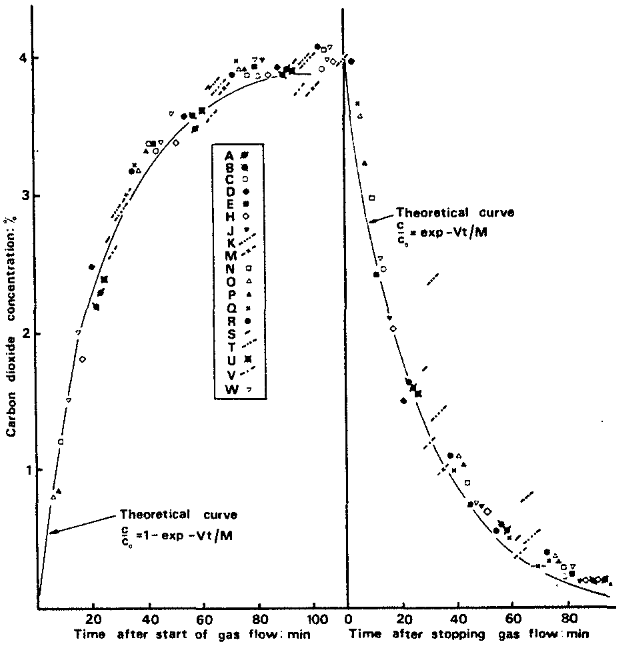


Fig. 11. *Variation of carbon dioxide concentration with time at positions shown in Figure* 9.

Ventilation rate $2\frac{1}{4}$ RV/H.

In the first experiment the flow rate through the inlet grill was set to give 80 m^3 of carbon dioxide–air mixture per hour, i.e. about $2\frac{1}{4}$ *RV/H*, and carbon dioxide was fed into the inlet at 0·22 l/sec for 4 hr 50 min. Figure 11 shows the variation of concentration with time at the positions marked in figure 9. The experiment was repeated with the flow rate reduced to 2/3 *RV/H* and a carbon dioxide flow rate of 0·20 l/sec, the results being plotted in figure 12.

The carbon dioxide flow rates were chosen to give average concentrations in the inlet duct of about 4 per cent by volume in the first experiment and about 2·8 per cent in the second, thus increasing the density of the incoming air by about 2 per cent. The carbon dioxide supply was continued until these equilibrium concentrations prevailed throughout the room. In both experiments the measurements of carbon dioxide concentration were continued after the carbon dioxide supply had been switched off and the results are also shown in figures 11 and 12.

The results of both experiments show that the variation of concentration with time at each measurement point is approximately independent of its position in the room, even though some of the measurements are far from the air inlet in corners, above cupboards and under a table. It can therefore

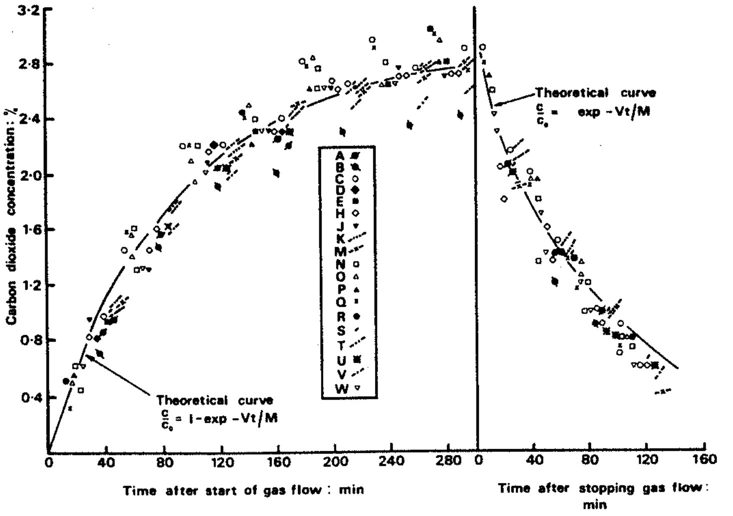


Fig. 12. *Variation of carbon dioxide concentration with time at positions shown in Figure* 9.
Ventilation rate $\frac{2}{3}$ RV/H.

be concluded that in this case essentially instantaneous mixing of incoming air and the air within the room takes place due to the turbulent convection from windows, heaters and the motions induced by the incoming jet. This applies approximately even for the low ventilation rate of $2/3\ RV/H$. The theoretical results from figure 8 are also shown in figures 11 and 12 and can be seen to be a good fit to the experimental results. Since the theory assumed instantaneous mixing throughout the space this is further confirmation that the ventilation reaches all parts of the room. The appropriate curve from figure 8 to apply to these experiments is the curve for $q/V = 0$ [equation (3)] since there is no fresh air supply, the carbon dioxide being introduced directly into the ventilating air.

MEASUREMENT OF THE FRESH AIR INPUT USING A STEADY FLOW OF TRACER GAS

The usual technique of obtaining the ventilation rate (fresh air input) in buildings [6] is by measurement of the dilution of tracer gas at one or more points in the room, assuming the incoming air mixes instantaneously with the air in the room during the dilution process—an assumption demonstrated to be true in some cases by the experiment described above. In the standard technique the tracer gas is injected over a short period and only the decrease in concentration is measured. This method can not be improved upon when the only information of interest is the total rate of input of fresh air into a room. However, where ventilation is intended to enter through one opening alone—as is usually the case with mechanical ventilation—the tracer gas dilution technique will not distinguish between that ventilation and adventitious ventilation through cracks etc. A new technique based on that used to investigate mixing in the experiment described in the section above can be used to distinguish between the main ventilation through an input grille (or grilles) and the adventitious ventilation. If a tracer gas is fed at a steady rate into the intended ventilation inlet (or inlets) and the build-up of concentration with time measured at a point in the room the build-up in concentration can be compared with figure 8 and hence the total fresh air input to the room determined—the measurement and calculation are essentially the same as with the standard technique except that a build-up, not a decay in concentration is observed. A single measurement of concentration, c' at the outlet grille (easily made by the same technique as used for the measurements in the room space) adds greatly to the information. Firstly, it gives the ventilation rate q' through the grille since

$$q'c' = V c_o$$

and secondly if c' differs significantly from the concentration predicted by figure 8 as the final asymptotic value of room concentration a second route for the entry of fresh air into the room space exists and the adventitious ventilation rate can be calculated from the difference between the total fresh air rate obtained from figure 8 and the ventilation rate through the grille. If the concentration in the room at any time is greater than that measured at the inlet grille at the start of the release of tracer gas, recirculation is taking place—a further useful piece of information of interest in some ventilation systems. An important point in using the technique is that good mixing between the tracer gas and ventilation in the grille must be assured by injecting the tracer gas some distance upstream from the outlet or by using a tracer gas inlet system designed to give ready mixing with the ventilation.

STRATIFIED LAYERS

This section is concerned with the situation where buoyancy predominates and mixing is inhibited. The discussion will be with reference to methane as this is the gas most likely to form stratified layers in buildings in the future due to its widespread use. Similar arguments will apply to any gas lighter than air although there are only two of interest, hydrogen and ammonia. With gases and vapours heavier than air stratified layers can also form against the floor and similar arguments will apply with the sign of the buoyancy force reversed.

Methane is lighter than air (the density difference between methane and air, divided by the air density, $\Delta\rho/\rho$, is equal to 0·44) and will therefore tend to rise and accumulate on the underside of a roof (unless the leak is at the roof when the flow can, of course, only be along the roof and downwards). Thus there will be a tendency to form roof layers. When a roof layer has formed it may be extremely difficult to mix the contents of the layer with the air beneath.

Influence of buoyancy on mixing by turbulence—The Richardson Number

If we have two fluids of different density, with the lighter fluid on top of the heavier one, work must be done in order to mix the two fluids. The amount of work which must be done when a unit volume of the light fluid is lowered, and a unit volume of the heavy fluid is brought up to replace it, is equal to the product of density difference, gravitational acceleration, and the vertical distance of displacement. Alternatively, one might say that the potential energy of the system is being increased when the light and the heavy fluid mix, and that work equal to the change in potential energy must be done.

Consider now the situation when the two fluids are moving, and when they are mixing by turbulence. This situation was analysed and expressed mathematically by Richardson [7, 8]. In order to sustain the mixing by turbulence of the light fluid and the heavy fluid, work must be done on the fluids at a rate equal to the rate of work done against gravity. In the main, this work is done by the turbulent stresses in the flow. The rate at which the turbulent stresses work on a unit volume of fluid per unit time is equal to the product of the turbulent stresses and the difference of velocity at the boundaries of the fluid element. From Richardson's analysis, the ratio of the work done against gravity to the work done by the turbulent stresses is expressed by

$$\frac{-\dfrac{g}{\rho}\cdot\dfrac{\partial\rho}{\partial y}}{\left(\dfrac{\partial u}{\partial y}\right)^2} \tag{8}$$

where g is gravitational acceleration, ρ is density, $\partial\rho/\partial y$ is the rate of change of density with vertical distance, and $\partial u/\partial y$ is the rate of change of velocity with vertical distance.

Expression [8] is named the Richardson number. It is the fundamental parameter of turbulent diffusion on stratified fluids. If the Richardson number is large it means that the work done against gravity is large compared to the work which can be done by the turbulent stresses. In consequence, the rate of turbulent mixing which can be sustained may be greatly reduced, and may subside altogether. If the Richardson number is small, on the other hand, the work done against gravity is only a small part of the work being done by the turbulent stresses and consequently the buoyancy will have only a small effect on the rate of mixing by turbulence.

It is therefore possible for a buoyant layer to be turbulent, for the air beneath it also to be turbulent, but for little turbulent diffusion and hence dilution of flammable gas to be taking place. We are not able to calculate the Richardson number for the conditions found in buildings and show that it is large enough for turbulent mixing to be inhibited. We shall examine the consequences arising from layers mixing only by molecular diffusion and shall therefore compare the results of the calculations, which are made possible by the assumption, with experiment and in this way establish that the assumption is reasonable for some situations of practical interest.

Dilution by molecular diffusion

A condition will be considered assuming no turbulent diffusion. Let us assume steady state conditions with a steady gas leak and ventilation extracted continuously at some level in the room, i.e. extract ventilation from a grill at a distance y_0 from the roof (see figure 13) and a supply of gas to the roof at a steady rate of flow V at a concentration c_0 (this could arise either from a leak in the roof space passing through a false ceiling or from a low level gas leak flowing by buoyancy to the roof in a manner to be discussed later). Contours of constant concentration will tend to be horizontal because buoyancy will act to straighten out any irregularity. At the bottom of the layer, gas will be removed and pass out through the extract grill. Thus at the level of the grill we shall assume that the concentration is zero.

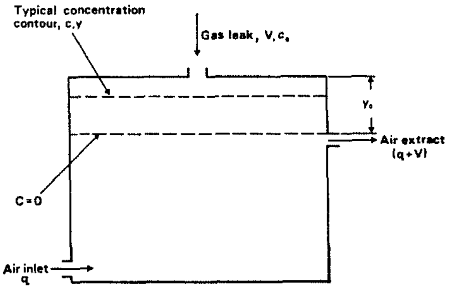


Fig. 13. *Flow diagram for calculations of roof layer concentration.*

This situation is similar to that considered by Titman, Roberts and Brookes [9], who calculated the concentration in a roof cavity into which methane was fed with a turbulent ventilation flow passing underneath the cavity, except that in our case the ventilation and the layer are both in the same space, the room. When a steady state is reached (concentration independent of time) the rate of flow of methane across any horizontal plane above the outlet grill is equal to the rate of input of methane Vc_o so

$$Vc + DA\left(-\frac{dc}{dy}\right) = Vc_o \qquad (9)$$

where D is the coefficient of molecular diffusion of methane into air and A is the cross-sectional area of the room and y is the vertical distance from the ceiling. The first term on the left hand side of [9] represents the bulk flow and the second term represents the molecular diffusion.

The boundary condition we have assumed is that at $y = y_o$, $c = 0$ and integration gives

$$\frac{c}{c_o} = 1 - \exp\left[-\frac{V}{AD}(y_o - y)\right] \qquad (10)$$

(This solution applies to any rooms with vertical walls, but rooms other than rectangular cross section are rare).

It will be noticed that at $y = o$, i.e. at the ceiling, the concentration is not equal to the input concentration as might be expected at first sight. This follows from the assumption that the concentration at the extract is zero and depends on the fact that there is a finite amount of molecular diffusion at the ceiling. Experiments performed here and those performed in roof cavities by Titman, Roberts and Brookes [9] provide good agreement with the theory based on the above boundary condition.

Equation (10) has been evaluated for a ventilation outlet 0·3 m below the roof for three values of V/A: 0·1, 1 and 10×10^{-4} m/sec and the variation of concentration c/c_o with distance below the roof is plotted in figure 14. The lower flammable limit of 5 per cent is indicated. It can be seen that flammable layers are formed in all cases.

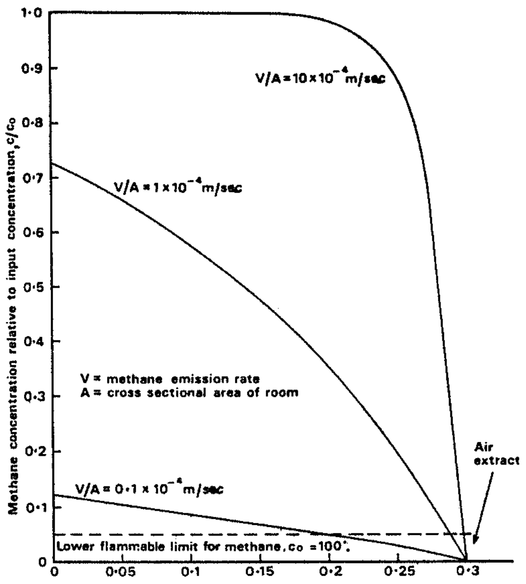


Fig. 14. *Theoretical variation of methane concentration in roof layers with distance below roof with extract ventilation* 0·3 m *below roof.*

In addition to figure 14 the solutions of equation (10) are presented in Table 3 for a wider range of flow rates.

As an example of how to use figure 14 let us assume a gas leak of 10 l/sec in a room of cross-section 10 m²: $V/A = 10 \times 10^{-3}/10 = 10 \times 10^{-4}$ m/sec and the upper curve gives the resulting concentration distribution. Flammable gas extends

Table 3. *Values of methane roof layer concentration in steady state:* c/c_0

Distance above extract y (M)	Methane emission/Unit area of room: V/A (m/sec × 10^4) 0·01	0·05	0·10	0·25	0·50	1·00	2·00	5·00
0·00 (Extract)	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
0·05	0·00	0·01	0·02	0·05	0·10	0·20	0·35	0·66
0·10	0·00	0·02	0·04	0·10	0·20	0·35	0·58	0·89
0·15	0·01	0·03	0·06	0·15	0·28	0·48	0·73	0·96
0·20	0·01	0·04	0·08	0·20	0·35	0·58	0·82	0·99
0·25	0·01	0·05	0·10	0·24	0·42	0·66	0·89	1·00
0·30	0·01	0·06	0·12	0·28	0·48	0·73	0·93	1·00
0·35	0·02	0·07	0·14	0·32	0·53	0·78	0·95	1·00
0·40	0·02	0·08	0·16	0·35	0·58	0·82	0·97	1·00
0·45	0·02	0·09	0·18	0·39	0·62	0·86	0·98	1·00
0·50	0·02	0·10	0·20	0·42	0·66	0·89	0·99	1·00
0·55	0·02	0·11	0·21	0·45	0·70	0·91	0·99	1·00
0·60	0·03	0·12	0·23	0·48	0·73	0·93	0·99	1·00
0·65	0·03	0·13	0·25	0·51	0·76	0·94	1·00	1·00
0·70	0·03	0·14	0·26	0·53	0·78	0·95	1·00	1·00
0·75	0·03	0·15	0·28	0·56	0·80	0·96	1·00	1·00
0·80	0·03	0·16	0·29	0·58	0·82	0·97	1·00	1·00
0·85	0·04	0·17	0·31	0·60	0·84	0·98	1·00	1·00
0·90	0·04	0·18	0·32	0·62	0·86	0·98	1·00	1·00
0·95	0·04	0·19	0·34	0·64	0·87	0·98	1·00	1·00
1·00	0·04	0·20	0·35	0·66	0·89	0·99	1·00	1·00

V = methane emission rate, m³/sec
A = cross-section area, m²
y = height above datum (extract), m
c = methane concentration, %
c_0 = methane concentration at input to roof, %

more than 0·29 m below the roof and the concentration is 0·9 (i.e. 90 per cent for 100 per cent methane at source) for the upper 0·25 m.

EXPERIMENTS

In order to see if the assumptions made in deriving equation (9) and applying it to gas layers in buildings lead to results of practical importance, and to explore the situation where the assumptions begin to become invalid, experiments were carried out using the experimental facility described by Daws, Penwarden and Waters [10]—this consisted of a room (figure 15) 2·7 × 3·7 × 3·7 m. In these experiments air was extracted through a slot and fresh air put into the room through a circular diffuser in the roof. In the present experiments the floor was covered with a gauze placed 0·05 m above the floor and into the space beneath this gauze a measured flow of nitrous oxide could be released. The ventilating air was extracted through a slot which was set at two heights above the gauze, 0·27 and 0·16 m. The ventilation extract rate could be varied from 0·5 to 7 *RV*/*H*.

In the experiments it was arranged for the air extracted from the room not to be recirculated into the room. A calibrated orifice plate was used to measure the air extract rate. The dimensions of the slot are height 2 cm and width 48 cm. The relative density difference between nitrous oxide and air is numerically equal to that for methane and air except that the nitrous oxide is heavier than air. The conditions of the experiment correspond to a gas leak entering a room through a porous ceiling, except that the experiment is conducted upside down. The molecular diffusion coefficients of nitrous oxide and methane differ so the concentration distribution will not be identical for the two gases.

Figure 15 shows how the gas concentration was measured. The plan view shows the positions where sampling pipes were placed in a vertical array to cover the expected height of the layer.

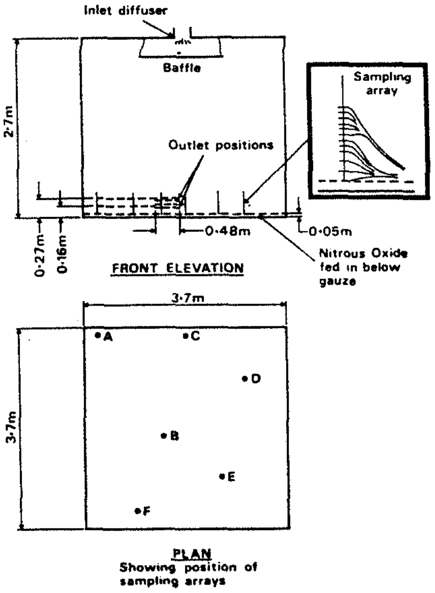


Fig. 15. *Room for layering experiments.*

The purpose of measuring at six places across the cross section was to determine if the assumption made in the theory that concentration contours are horizontal planes was justified. At each sampling position were 12 horizontal pipes of diameter 2 mm from each of which a sample could be pumped to a thermal conductivity analyser. There were therefore a total of 72 sampling positions available for each experiment. However, in a typical experiment all the sampling positions were not used. The procedure was to take the top measuring position from one sampling array, the second measuring position from another, the third measuring position from yet another and so on. The results were then plotted on a single curve. An example of this is given in figure 16. If the concentration contours are horizontal then measurements made in this way will fall on a single curve with only a small experimental scatter and there is no need to determine each concentration profile in detail. In fact, the experimental scatter was small in all of the experimental measurements made, even at the highest ventilation rates, and the first conclusion is therefore that this major assumption of horizontal concentration contours was justified.

Figure 16 shows a series of experiments carried out with the air extract 0·27 m above the gauze, and with a nitrous oxide release into the space below the gauze of 2 l/sec. Figure 16 also shows the theoretical results calculated from equation (10). It can be seen that for an air extract of 0·5 *RV*/*H* the theory and experiment are in good agreement. It can also be seen that as the air extract rate is increased to 2·8, 4 and 6·6 *RV*/*H* the theoretical results begin to differ from experiment and there is some dilution of the layer occurring due to the ventilation. However, the concentrations are still

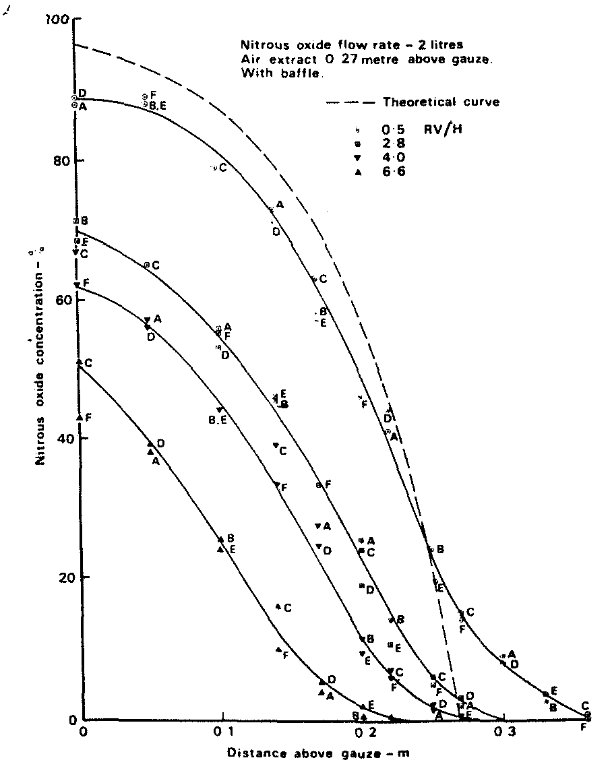


Fig. 16. *A comparison of theory and experiment and also the effect of ventilation on a nitrous oxide layer.*

high and layering is present and at an air extract of 6·6 *RV/H* the concentration at the floor (gauze) is 50 per cent. A possible explanation for the reduction in concentration with increased ventilation may be that the effective height of the air extract is lowered as the flow rate increases, the gas layer being drawn with it from a lower level than the extract since the sphere of influence of any extract increases with increasing flow. It is therefore likely that even at the higher ventilation rates turbulent dilution does not occur.

A roof baffle was included because it was thought, from preliminary flow visualisation studies, that the downward jet from the centre of the diffuser may have a disturbing influence on the centre of the layer leading to distorted concentration contours. Experiments were carried out to see if this baffle was affecting the behaviour of the layer and the results are shown in figures 17 and 18. The experiment used as before an air extract 0·27 m above the gauze and ventilation rates of 0·8 and 2·7 *RV/H* with nitrous oxide flow rates of 2 and 1 l/sec respectively. It can be seen that the results are virtually identical with and without the baffle and figure 17 shows good agreement with the theoretical results. It can therefore be concluded that the stabilising effect of buoyancy was so great that for both of these ventilation rates and inlet arrangements the concentration contours were not distorted. The same results were obtained for two different air inlet conditions suggesting that the results of these experiments will be applicable to some practical situations.

Figures 19 and 20 show a similar series of experiments to those in figure 17 for nitrous oxide flow rates of 0·25 and 1 l/sec respectively. Once again the conclusions are similar, the theoretical result agrees approximately with the experiments for the low ventilation rates and the effect of high ventilation rates on the layer is small in that the layering is not eliminated. For the lowest flow rate, 0·25 l/sec, it can be seen that for a ventilation rate of 2·8 *RV/H* a well defined layer is still formed although the magnitude of the concentration is reduced. At 5·9 *RV/H* there are signs of the beginning of break-up of the layer although concentrations are still fairly high—up to 9 per cent at the floor.

Figure 21 shows a series of experiments carried out with the air extract height reduced to 0·16 m above the gauze and once again the main conclusions are the same but with the distance above the gauze at which the concentration reaches zero reduced in accordance with the reduced extract height, as the theory predicts.

Figure 22 compares theoretical curves and experimental curves for two flow rates, the ventilation rate being 0·8 *RV/H*, and once again good agreement is obtained.

It can therefore be concluded that the theory can be used to predict the upper limit of concentration of gas in roof layers in buildings for gas leaks at or near the roof with ventilation extracted at a known distance below the roof through windows, cracks or extract grilles. Table 3 gives theoretical results for a wide range of practical conditions and this can be used as a design chart to predict layer concentration for alternative positions of an air extract.

For a given value of leak rate per unit area of room cross-section the value of the concentration at any height in the layer may be found from Table

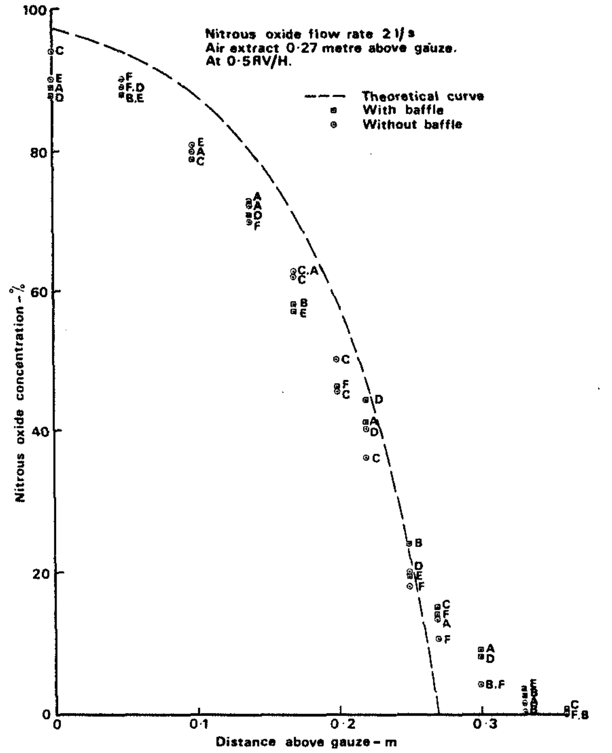


Fig. 17. A comparison of theory and experiment showing the effect of varying the air inlet geometry for a nitrous oxide layer.

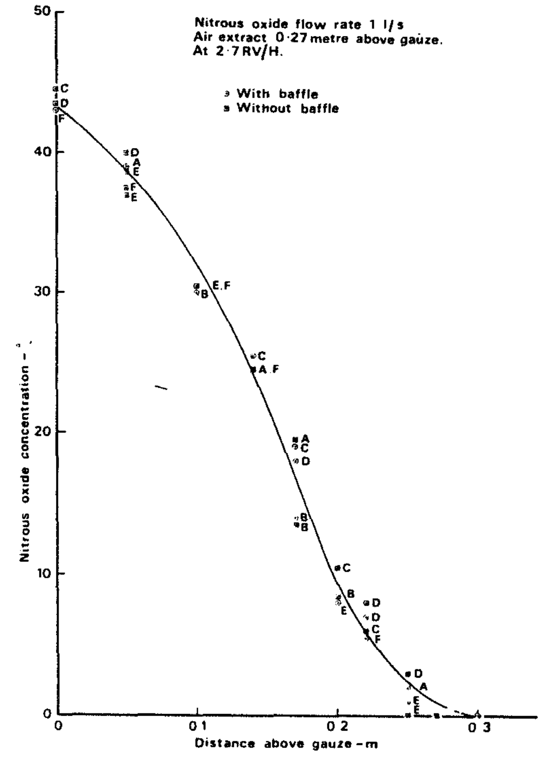


Fig. 18. An experiment showing the effect of varying the air inlet geometry for a nitrous oxide layer.

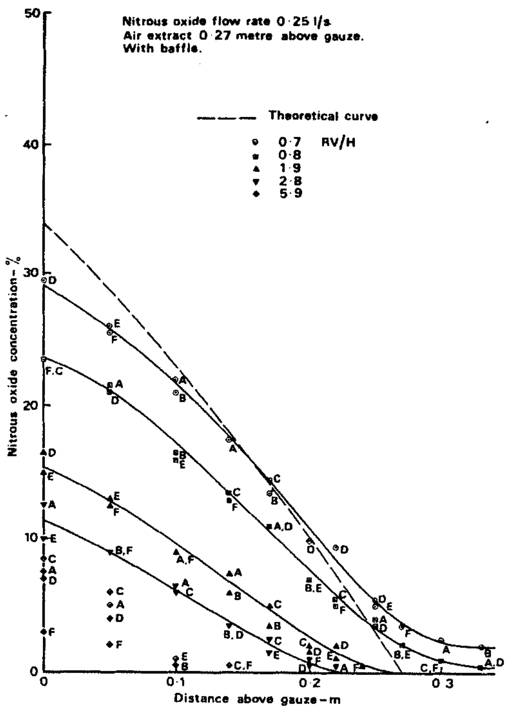


Fig. 19. *A comparison of theory and experiment, showing the effect of ventilation on a nitrous oxide layer.*

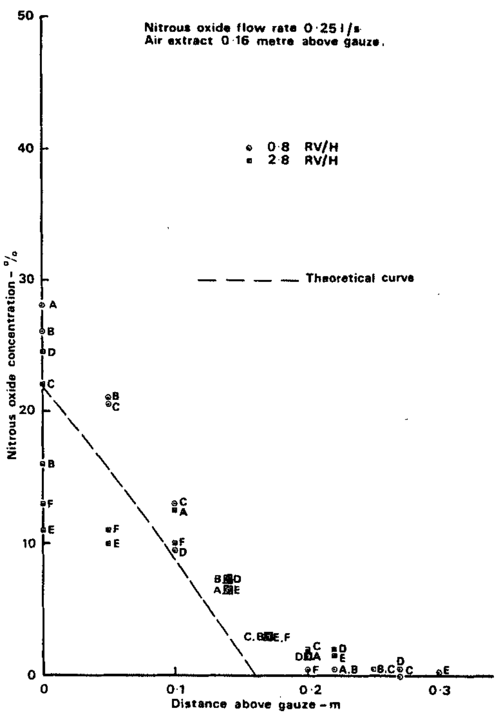


Fig. 21. *A comparison of theory and experiment, showing the effect of ventilation on a nitrous oxide layer.*

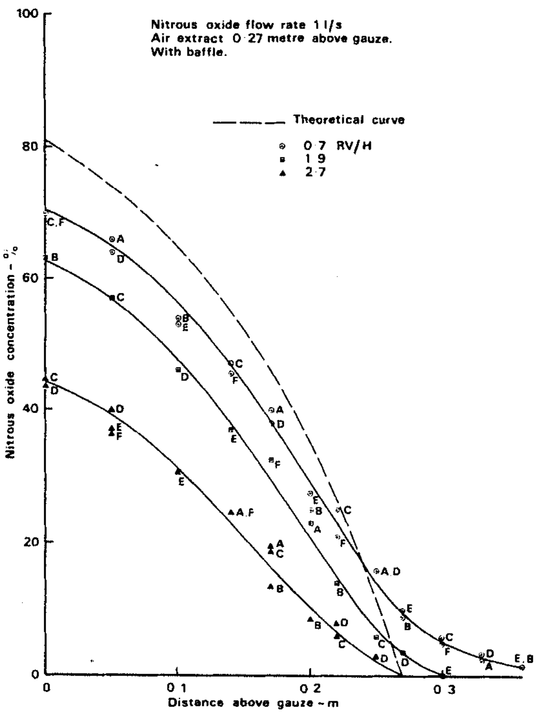


Fig. 20. *A comparison of theory and experiment, showing the effect of ventilation on a nitrous oxide layer.*

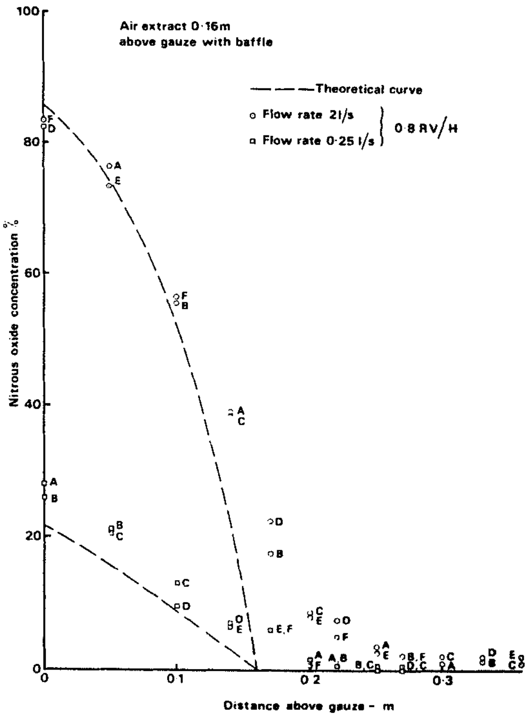


Fig. 22. *A comparison of theory and experiment for two flow rates of nitrous oxide.*

3 as follows. The concentration profile for a ceiling-extract distance of h is given by entries in the table of $y \leq h$, e.g. for a flow rate of 1 l/sec into a room of cross-sectional area 10 m^2 we have $V/A = 10^{-4}$ m/sec and so we look under the column V/A (m/sec $\times 10^4$) = 1·00. If the extract-ceiling height is 0·60 m then the ceiling concentration will be given by the entry $y = 0{\cdot}60$ i.e. $c/c_o = 0{\cdot}93$ or $c = 93$ per cent for $c_o = 100$ per cent. Similarly the concentration at a distance half way between the ceiling and the extract will be given by $y = 0{\cdot}30$ giving $c = 73$ per cent for $c_o = 100$ per cent.

The maximum allowable distance of the extract from the roof can therefore be determined for a given gas leak, using the criterion that the maximum concentration (equal to that at the roof) is 5 per cent.

However a layer which just reaches 5 per cent at the roof would be unlikely to be harmful on ignition and, as outlined later, there will be a volume of flammable gas below which injury (burning) or structural damage will not occur on ignition. When the magnitudes of such volumes have been established from studies outside the scope of this paper it will also be possible from integration of equation (10) to find the maximum allowable distance of an extract from the roof.

MIXING OF GAS FLOWING VERTICALLY UNDER BUOYANCY

In many practical situations a gas leak will not take place from a source at or near the roof. The leak may be, as was thought to have happened at Ronan Point, from a severed gas pipe near to the floor. The gas will then rise towards the roof under the action of buoyancy. During this vertical flow the gas will be mixing readily with the air because buoyancy is not acting to oppose the turbulent diffusion. Smoke rising from a cigarette forms a conical shaped plume in calm conditions. This is a buoyant plume similar to that from a gas leak as the temperature difference between the smoke and the surrounding air causes a density difference. The plume is initially in a laminar flow but a short distance above the cigarette the flow can be seen to break up and become visibly turbulent.

We shall now outline the theory of Morton, Taylor and Turner [11], extend their treatment of finite sources and describe some sample experiments using nitrous oxide. The experiments are not extensive as experiments on buoyant plumes have been made by Morton, Taylor and Turner. The present experiments apply to conditions which may arise in dwellings and merely demonstrate the relevance of the general approach to these particular conditions.

Consider the vertical flow of a gas with a density less than that of air. As the plume rises it will entrain air from its surroundings due to turbulent mixing and thus the density difference between it and its surroundings, and hence also the gas concentration, will decrease. However, the buoyant upthrust on the plume will remain constant.

Morton, Taylor and Turner [11] considered this case and derived the conservation equations:

$$\frac{\mathrm{d}}{\mathrm{d}y}(b^2u) = 2\alpha bu \quad \text{(volume)} \qquad (12)$$

$$\frac{\mathrm{d}}{\mathrm{d}y}(b^2u^2) = 2b^2g\left(\frac{\rho_o-\rho}{\rho_1}\right) \quad \text{(momentum)} \qquad (13)$$

$$\frac{\mathrm{d}}{\mathrm{d}y}\left[b^2ug\left(\frac{\rho_o-\rho}{\rho_1}\right)\right] = \frac{2b^2ug}{\rho_1}\cdot\frac{\mathrm{d}\rho_o}{\mathrm{d}y} \quad \text{(buoyancy)} \qquad (14)$$

where

b is the horizontal distance from the plume axis at which the velocity has fallen to a value 1/e times the axial velocity.

$u(y)$ is the axial, vertical velocity in the plume at a height y.

α is the entrainment constant, taken to be 0·08 (see Morton [12])

y is the vertical distance from the source.

ρ_o is the density of air.

ρ is the axial density in the plume.

ρ_1 is a reference density which we shall take as ρ_o.

g is the acceleration due to gravity.

The assumptions involved include the following:

(a) The rate of entrainment to the plume at a given height is proportional to some characteristic velocity at that height.

(b) The profiles of velocity and buoyancy in horizontal sections of the plume are of similar form at all heights, i.e.

$$u(y, r) = u(y)\,\mathrm{e}^{(-r^2/b^2)}$$

where r is the radial distance from the plume axis.

(c) The variations in density are small compared with the reference density.

They solve these equations for a point source and this solution leads to a value of the gas (density ρ_g) concentration at a height y of:

$$c(y) = \frac{\rho_o}{g(\rho_o-\rho_a)}\cdot\frac{5Q}{6\alpha}(1{\cdot}8\,\alpha Q)^{-1}/3.{}_{y}{}^{-5/3} \qquad (15)$$

where

$$Q = g\frac{(\rho_o-\rho)}{\rho_o}\cdot b^2u \qquad (16)$$

The above solution implies conditions at the source such that the density difference is infinite (see Appendix). This may be avoided by extending the above to cover the case of a finite source. To do this, change the variables to $w = b^2u$, $z = bu$ and, noticing that ρ_o is constant, integrate (14) with respect to y. The quantity $(\rho_o-\rho)/\rho_1$ may then be eliminated between (12) and (13) giving the result:

$$\frac{\mathrm{d}w}{\mathrm{d}y} = (Aw^2+B)^{1/5} \qquad (17)$$

where A and B are constants.

The case of a point source is recovered by putting $B = 0$, leading to the solution (15) (see Appendix). If $B \neq 0$, i.e. a finite source, then an analytic solution cannot be obtained. Results for this case have been obtained by numerical integration of (17) and figures 23 and 24 compare these with experimental results for two rates of leakage of nitrous oxide, 0·25 and 1·0 l/sec: the rapid reduction of concentration with distance above the source predicted is observed, although in general, the experimental results show slightly higher concentrations than those predicted by the theory.

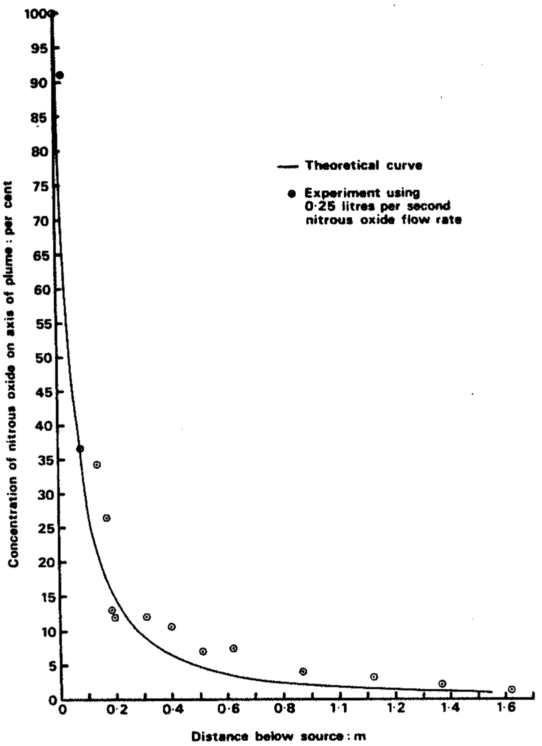


Fig. 23. A comparison of theory and experiment using nitrous oxide for buoyant plumes.

As a buoyant jet rises in a room and reaches the ceiling, it will spread uniformly over it in much the same way as water will spread if poured onto a flat surface. The theoretical results for the maximum (axial) methane concentration in plumes are shown in figure 25 for a wide range of gas leakage rates (0·01–5·0 l/sec) for distances above the source of the leak of 0·5–2·0 m and can be used to give the maximum concentration reaching the roof which will be equal to the concentration over the entire ceiling.

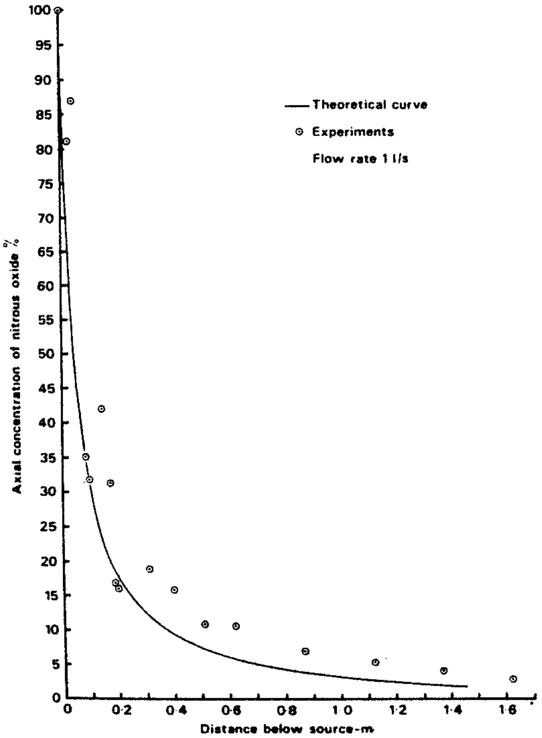


Fig. 24. A comparison of theory and experiment using nitrous oxide for buoyant plumes.

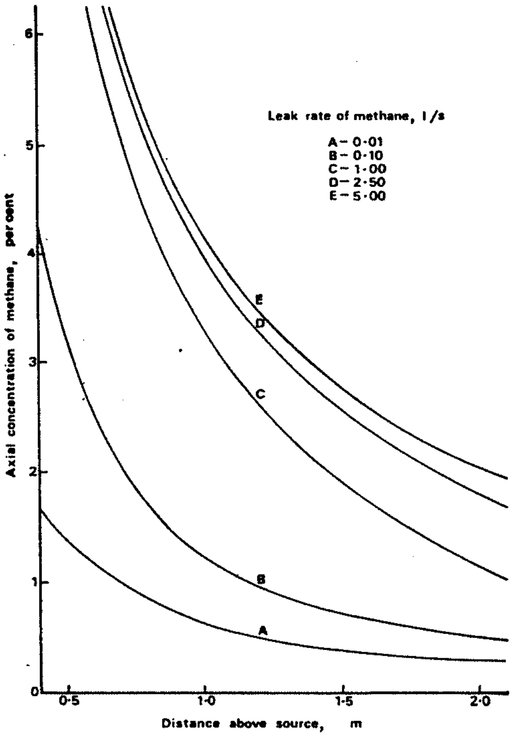


Fig. 25. Theoretical concentration in plumes: concentration of methane on plume axis vs height above leak for a wide range of leak rates.

If the source is placed near walls or other surfaces, as in the case of a gas standpipe, then the foregoing theory cannot be expected to apply as the presence of the wall implies different boundary conditions. The entrainment will be reduced and to get an approximate answer for practical problems it is suggested that the concentrations predicted by the theory are increased by a factor of about two. This is no more than a rough estimate but it would apply in symmetrical conditions with the pipe against the wall. We only carry out experiments to demonstrate that the basic mechanism and theory apply to the buoyant plume.

It can be concluded from these calculations, that a gas source low down in a room, for most gas release rates, will be so diluted during its vertical flow that high gas concentrations will not be reached. This is an important conclusion and explains why in many practical situations, for example at Ronan Point, a high concentration of methane was not reached. This dilution arises entirely from the convective flow of the gas itself and is not a consequence of ventilation.

As the plume rises and entrains air the concentration of gas in the plume decreases and the width of the plume increases in such a way that the total volume flow of methane across any plume cross-section remains constant. This amounts to a statement of the continuity equation.

It is important here to realise that the time for which we can safely use the results quoted in some situations is small. This may be explained as follows: we are dealing with a confined space where the gas reaching the ceiling forms a layer by diffusing downwards (coupled with a bulk flow necessary to prevent fluid at the ceiling from being compressed).

The existence of this layer soon invalidates the assumptions made in deriving the results quoted i.e. we no longer entrain air but a mixture of air and methane into the plume, over the height of the layer. This will result in an increase in the concentration of methane in the plume and hence in the concentration at the ceiling and throughout the room. This situation has been considered by Baines and Turner [13] who studied the buoyant convection from point sources in confined spaces and made allowance for the build-up of material in the space. The calculation of the concentration at a stated time from their results is complex and cannot be put in the form of simple rules for ventilation design as has been done for the other situations considered in this paper. However the results of Baines and Turner could be used for specific situations such as may arise in investigations associated with a particular explosion.

At Ronan Point the layer could form until reaching the door lintel and then it could flow underneath and occupy the space above the lintel throughout the rest of the flat, e.g. hall and bedroom, and fresh air would be displaced into the kitchen. We may conclude that the results obtained above could apply for an appreciable time to the situation at Ronan Point.

We have now explained the main features of the gas accumulation at Ronan Point. The concentration of gas emanating from a source behind the gas cooker in rising to the roof would be diluted to a few per cent by the action of its turbulent convective flow. Once at the roof the gas could form a stably stratified layer, low ventilation would be insufficient to overcome the action of the buoyancy and the layer could increase in thickness until it reached the height of the open door and passed beneath the top of the door. The gas would then continue to build up in the kitchen and in the connecting rooms. We can therefore see how the ventilation entering the kitchen could fail to directly dilute the gas in the layer and how this layer could build up throughout the flat.

THE ACCEPTABLE SIZE FOR GAS ACCUMULATIONS AND THEIR DETECTION

In this section no firm conclusions will be reached because the definition of acceptable volumes of flammable gas needs much more study. An attempt will be made to indicate the factors that need to be considered in such studies.

When a layer is ignited several hazards arise: it could lead to burning of people or the building, it could lead to a person being knocked over or shocked, or it could lead to a sufficiently violent explosion for serious structural damage to occur. A different size of acceptable accumulation would arise for each hazard.

The pressure produced on ignition depends on many factors: for example the volume and properties of flammable gas present and its concentration, the degree of pressure relief or venting, the length of the layer, the detailed geometry and roughness of the building and the possibility of pressure piling. The length of the layer is important because combustion causes the gases to expand, this sets up flows ahead of the flame which tend to make the combustion turbulent and the flow accelerate. Thus the flame, in long layers which are thick enough, and against surfaces or in situations rough enough to produce turbulent flow, will increase in speed and become more violent the longer the layer. Pressure piling can arise when flammable gas is present in two connecting rooms: an explosion in the first room raises the pressure in the second and the following explosion there takes place at a higher pressure. Such phenomena are known in coal mine explosions but because of the complex processes involved it is often impossible to predict the resulting pressures. We cannot therefore define an acceptable accumulation for avoiding major damage to buildings without extensive studies in them. Some progress for a limited range of conditions has been made in studies of explosions by Astbury, West, Hodgkinson, Cubbage and Clare, [14].

Situations which may lead to particularly hazardous explosions in the future are gas leaks above false ceilings and in long tunnels or near horizontal service ducts. An example of a violent explosion in a tunnel from the ignition of a long layer took place in Japan in 1970 which killed at least 76 people, injured 240 and started a series of fires that damaged 30 buildings [15].

Studies by Bakke and Leach [16] and Leach and Barbero [17] make it possible to predict the length of layer resulting from leaks in ventilated service tunnels. These papers give a general theory and many experimental examples and for this reason the subject is not covered in the present paper.

Detection of gas layers

In order to be certain that a serious gas accumulation is detected it is first of all necessary to know the size of the accumulation that presents a hazard. In a large space such as that between a false ceiling and a roof it is possible for a gas accumulation to form which is many times larger than that which would not produce major structural damage. It would be necessary to place detectors at intervals throughout this space to be sure that the hazardous accumulation would be detected, the spacing between them determined by the minimum size of acceptable accumulation. Clearly very many detectors may be needed for large spaces. If we consider a complex building of many rooms gas detectors may be needed in each room in which a gas layer could form or, at least, originate.

Where air is extracted with common duct systems, such as described by Wise [18], a single gas detector could protect a number of spaces. A detector here would need to be much more sensitive as the gas would be diluted by the flows from rooms without a gas leak.

A system which may be appropriate for some situations would be to extract a small flow through a pipe leading to an inlet at a high point in each of the spaces of interest and passing the sample through a single detector in turn. Fail-safe systems would be essential if reliance was placed on detection.

Furthermore, if a gas accumulation is detected it is necessary to ensure that action follows detection and that some means of removing the gas safely is provided. Both of these steps would require complex organisation for the domestic situation.

MAIN CONCLUSIONS

The conclusions can be summarised following two classifications: (a) situations of low Richardson number in which buoyancy has a negligible effect on turbulent mixing and the ventilation and contaminating gas or vapour mix readily together, classified as "Instantaneous mixing" and (b) situations of high Richardson number in which buoyancy stabilisation predominates, stratified roof or floor layers form and mixing takes place only by molecular diffusion, classified as "Layering". Situations which lie between these two extremes involve complex mixing processes and it is unlikely that a general theoretical solution will ever be obtained covering all possible situations in buildings. However, many important practical situations will fall into the two extreme situations (a) and (b) studied. In situations such as that thought to have obtained at Ronan Point the flow can be divided into two regimes: the gas rising from the leak to the roof mixes readily with the room air and can be classified under (a) but on forming a layer under the roof the subsequent mixing is of category (b).

(*a*) *Instantaneous mixing*

Two important aspects have been studied: (i) when the contaminating gas has the same density as the room air or the flows are sufficiently energetic for the buoyancy effects to be negligible and (ii) where the vertical motion of the contaminating gas itself under buoyancy is turbulent and mixes readily with the ventilating air. Theoretical and experimental results are given for both of these situations and are summarised in equation (7), figures 8, 14, 25 and Table 3, covering many situations of interest in buildings. Generally speaking, ventilation is a practical means of controlling the hazards in such situations and the ventilation requirements for control can be obtained from the design charts, given an estimate for the maximum credible gas or vapour leak and the acceptable conditions. Where a light gas is released near the floor the vertical motion under buoyancy can lead to low concentrations by the time the gas reaches the roof even in the absence of ventilation and the conditions leading to safe concentrations at the roof can be deduced from the theoretical results. This mechanism changes as the gas layer builds up and descends to an appreciable distance below the roof, as fresh air for dilution may no longer be available. In situations such as may have developed at Ronan Point, where the layer could flow under the door lintel, the above mechanisms may operate for some time.

(*b*) *Layering*

A light gas leak near a roof or in the space above a false ceiling can readily lead to a roof layer of flammable gas with high levels of ventilation having little effect on the layer. Theoretical calculations for situations with extract grilles near (but not in) the roof assuming no turbulent mixing of the layer with the ventilating air agree well with experiment and even with the extract ventilation rate increased to 7 room volumes/hr the roof concentration is such as to suggest that turbulent dilution does not occur. Theoretical results for a wide range of gas leakage rates, room sizes and extract location are given in figure 14 and Table 3. It is concluded that prohibitively high ventilation rates would be needed to control the gas hazards with an extract below roof level. The best arrangement is for the ventilation outlet to be actually in the roof for light gases and in the floor for heavy gases as suggested by Palmer, 1969 [19]. Such ventilation outlets would reduce the build-up of gas in spaces beneath buildings such as occurred at Clarkston, Glasgow.

Two situations where serious problems may arise in the future following current trends in building design and service layout are in the space above false ceilings and in near-horizontal common service ducts or tunnels.

It is not possible at the present time to deduce the size of acceptable accumulations of flammable gas. This is needed to be able to design ventilation and detection systems for controlling explosion hazards in layering situations using the theoretical results presented here and in general work on layering in ventilated tunnels, Bakke and Leach [16]. However the factors that need to be considered are outlined.

Acknowledgements—The work forms part of the research programme of the Building Research Establishment of the Department of the Environment and this paper is published by permission of the Director. The experiments on buoyant layers were carried out by Mr. R. A. Biddulph. The experiments using an office were carried out at the Department of Trade and Industry, Safety in Mines Research Establishment, Sheffield by Mr. H. Thompson.

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APPENDIX

The manipulations detailed on page 304 lead to the following values of the constants A and B:

$$A = 40Q\,\alpha^4 \qquad \text{(A1)}$$

$$B = (2\alpha z_o)^5 - Aw_o^2 \qquad \text{(A2)}$$

with Q defined as before:

$$Q = \frac{g(\rho_o - \rho)w}{\rho_o} = \text{constant} \qquad \text{(A3)}$$

where w_o and z_o are the values of w and z at $y = 0$.

For a point source the width of the source at $y = o$ is $b_o = o$ and in order to satisfy (iii) it is assumed that $w_o = b_o^2 u = 0$ and hence that $[(\rho_o - \rho)/(\rho_o)]_{x=o}$ is infinite. From (ii) it can be seen that for a point source $B = 0$ so that equation (17) reduces to:

$$\frac{dw}{dy} = (Aw^2)^{1/5}$$

and hence $w \propto y^{5/3}$ and $c \propto y^{-5/3}$ i.e. the result of equation (15) is obtained.