THE AIR OF FACTORIES AND WORKSHOPS.

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CONTENTS.

By the existing law for Great Britain it is enacted that "in every room in any factory or workshop sufficient means of ventilation shall be provided, and sufficient ventilation shall be maintained." Not very much has been hitherto ascertained, however, as to the degree of purity actually existing in the air of factories and workshops generally, or as to what standard of purity may reasonably be expected considering the difficulties met with. A Departmental Committee was recently appointed by the Home Secretary to investigate and report upon the subject. The members of the Committee were Mr E. H. Osborn, Engineering Adviser to the Chief Inspector of Factories, and myself, with Mr C. R. Pendock, one of H. M. Inspectors of Factories, as Secretary. The Committee has just reported on the subject of general ventilation[1], but reserving for a future Report the vitiation of air by dust, fumes, &c. from special manufacturing processes.

In the present paper I propose to give an account of the air of factories and workshops in the light of the facts ascertained by the Committee in the course of their experimental investigations on general ventilation.

[1] *Report of the Departmental Committee on Factory Ventilation, Parliamentary Paper,* 1902.

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Methods of Analysis.

Throughout the investigation the proportion of CO_2 in the air was mainly relied on as a measure of the impurity of the air. Although the slight excess of CO_2 (together with the corresponding deficiency in oxygen) in the air of inhabited rooms is in itself of no importance, it is certainly the simplest and most certain objective index of the probable proportion of those other impurities which cause air contaminated by persons and lights to be unwholesome.

The bleaching action of the air on permanganate solution has also been sometimes used as an index, but this method was not employed, as its significance is very uncertain, particularly as even in badly ventilated rooms most of the bleaching action is evidently due to smoke &c. present in ever-varying proportion in the outside air of towns. Even undiluted expired air has only a very slight bleaching action. As an average of twelve experiments the *excess* in bleaching action of expired air over inspired air was found to be less than the average bleaching action of outside air in Dundee[1].

To supplement the information obtained from CO_2 determinations the number of micro-organisms per litre of air was ascertained by us in a certain proportion of samples. When the number in outside air is small, as in winter or wet summer weather, this method gives results of some value, as where the amount of physical disturbance does not greatly differ in different rooms the number of bacteria in the air is a fair index of general cleanliness, and consequently of the probability of pathogenic bacteria being present. In many factories, however, large numbers of bacteria are present in the materials employed, and unless there is any reason to suppose that these materials may contain pathogenic bacteria not much importance can be attributed to the mere number of bacteria in a given volume of air.

The method employed for determining carbonic acid was described by me in this *Journal*, Vol. I. p. 109. The chief advantages of this method are, (1) that the analysis can be accurately carried out on the spot within less than five minutes; (2) that when samples of the air are collected for analysis at a more convenient time very small bottles are sufficient, and may be filled without loss of time. A bottle of 50 c.c. capacity permits of a double analysis being made.

To reduce the size of the apparatus, and render it more convenient, some modifications in the original apparatus were introduced: (1) The

[1] Carnelley, Haldane, and Anderson, *Philosophical Transactions*, 1887, B. p. 87.

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vessel within the case of the apparatus for holding the water used as a confining liquid in the analysis of bottle samples was dispensed with. An ordinary tumbler supported outside the case serves equally well if water is used. (2) The mercury reservoir was arranged so as to be supported by its neck from the front of the lower shelf of the case. With the saving of space thus effected the size of the case (internal measurements) was reduced to $12 \times 6\frac{1}{2} \times 2\frac{1}{2}$ inches[1].

For the collection of samples of air in bottles it was found best to employ dry and clean glass-stoppered bottles of about 50 c.c. capacity, as experience showed that bottles with ordinary corks coated with paraffin, as originally recommended, were not sufficiently tight if the sample was kept for long. The stopper of each bottle was lubricated with vaseline and held in position by an elastic band passing vertically round the bottle. A gummed label passing round the bottle over the elastic band secured the latter more firmly. On inserting the stopper it was turned round so that no air-channels were left in the vaseline.

In order to test this method of keeping samples the following experiments were made. The bottles used were of about 65 c.c. capacity.

I. Four samples of outside air (country) collected simultaneously in dry and clean bottles were kept for varying periods and then analysed.

			Vols. per 10,000.
Bottle 1.	Analysed at once	...	(a) 3·0
			(b) 3·0
„ 2.	„	after 5 days	2·8
„ 3.	„	„ 9 „	3·0
„ 4.	„	„ 19 „	(a) 2·8
			(b) 3·0

II. Five samples of air collected simultaneously in a room containing vitiated air were similarly kept and analysed.

			Vols. per 10,000.
Bottle 1.	Analysed at once	...	(a) 51·0
			(b) 51·4
			(c) 50·8
„ 5.	„	„ „ ...	50·8
„ 2.	„	after 2 days	51·2
„ 3.	„	„ 6 „	(a) 50·7
			(b) 51·0
„ 4.	„	„ 14 „	(a) 50·6
			(b) 50·4

[1] A detailed description of all the apparatus used is given in Appendix III. of the Report. The apparatus may be obtained from Messrs Müller, Orme, and Co., 148, High Holborn, London.

These experiments show that the carbonic acid does not increase or diminish within the bottles to an appreciable extent within a period much longer than would be required if the samples were sent away for analysis.

To test the effects produced by the bottles being wet or dirty the following additional experiments were made.

III. Four samples of outside air were collected in clean but wet bottles.

			Vols. per 10,000.
Bottle 1.	Analysed at once	...	3·0
„ 2.	„	after 3 days	(a) 2·4 (b) 2·2
„ 3.	„	„ 5 „	(a) 2·0 (b) 2·0
„ 4.	„	„ 12 „	(a) 0·2 (b) 0·0

IV. Four samples of vitiated air were collected simultaneously, two being in clean and dry bottles, and two in clean and wet bottles.

			Vols. per 10,000.
Bottle 1 (dry).	Analysed at once	...	(a) 20·6 (b) 20·8
„ 3 (dry).	„	after 9 days	(a) 21·2 (b) 21·2
„ 2 (wet).	„	at once ...	(a) 21·0 (b) 20·4
„ 4 (wet).	„	after 9 days	(a) 18·6 (b) 18·6

The last two experiments show that in bottles which were clean, but wet, a slow absorption of carbonic acid occurred. This was probably due to the presence of alkali dissolved by the water from the glass.

V. Five samples of outside air were collected in bottles which were dry, but very dirty from dust introduced.

			Vols. per 10,000.
Bottle 1.	Analysed at once	...	3·0
„ 2.	„	after 3 days	3·2
„ 3.	„	„ 5 „	(a) 3·2 (b) 3·0
„ 4.	„	„ 12 „	3·0
„ 5.	„	17 „	2·8

VI. Four samples of outside air were collected simultaneously in bottles which were both wet and very dirty from dust introduced.

			Vols. per 10,000.
Bottle 1.	Analysed at once	...	3·0
„ 2.	„	after 2 days	2·8
„ 3.	„	„ 6 „	(a) 8·0 (b) 7·6
„ 4.	„	„ 12 „	15·0

The last experiment shows that in bottles which are both wet and dirty the carbonic acid may increase very considerably within a short period.

The bottles used should be cleaned with a brush and water, and afterwards rinsed with distilled water and dried by heating. If alcohol and ether are used for drying very great care must be taken to remove the last traces of ether. Bottles used a second time require a fresh coating of vaseline round the stopper.

For the analysis of bottle samples mercury was used as a confining liquid. The stopper was removed under mercury in a small mortar, and the bottle, with its mouth closed by a finger, transferred to a trough similar to that described by me at p. 477, Vol. XXII. of the *Journal of Physiology*. The sample for analysis was then withdrawn through a curved tube into the air-burette. As, however, the sample was withdrawn at negative pressure, the mercury reservoir of the apparatus was depressed below the level of the table before the tap was closed, so that the pressure in the burette was positive when the reservoir was replaced on its hook. The excess of air was then let out by opening to the air an extra three-way tap inserted between the opening of the burette and the curved tube communicating with the bottle. The analysis could then be carried out without further trouble.

If water is used as the confining liquid only one analysis can be made from each bottle, as contact with water alters the proportion of carbonic acid after a short time.

For the determination of bacteria in air the method of Frankland[1], with a few slight modifications, was employed. According to this method a measured quantity of air is drawn through a sterile glass tube containing a plug of glass-wool or similar material. The brass syringe used for aspirating also measures the air. This plug, which arrests all the bacteria, is afterwards pushed out into a flask containing a small

[1] *Philosophical Transactions*, 1887, B. p. 113.

amount of Koch's nutrient jelly, previously sterilised, in which, when liquefied, the plug is disintegrated by shaking. The jelly is then cooled and allowed to become solid in a thin layer on the sides of the flask, which is kept at a temperature of about 20° till no more colonies develope. The modifications introduced were chiefly with a view to convenience. The glass tubes were shorter and somewhat narrower than those described by Frankland, and a second control plug was dispensed with, as Frankland's experiments showed it to be unnecessary. Each tube was sterilised in a separate outer tube closed by an asbestos plug. This was a great convenience, as the tubes could be carried in a cigar-case, and the handling of them was much simplified. The inner tubes were fixed directly by means of a junction of stout rubber to the brass syringe, the mercury gauge employed by Frankland being found unnecessary. Everything needed was thus very easily carried about. Finally, flat-bottomed bacteriological flasks were used for the jelly, instead of the ordinary flasks employed by Frankland. In this way the inconvenience due to liquefying colonies was greatly reduced. To facilitate the disintegration of the glass-wool plug the latter was crushed with a sterile glass rod against the bottom of the flask before the liquefied jelly was distributed.

Arrangement of Rooms and Ventilation in Factories.

In factories and workshops almost every variety in size and construction of rooms is met with; and the methods of ventilation, whether designed or accidental, vary correspondingly. As regards size the rooms which we visited varied from about 500 or 1000 cubic feet, as in small workrooms containing only two or three persons, to over 1,000,000 cubic feet with 1000 persons or more, as in some of the larger weaving or engineering sheds. In construction also the rooms varied greatly. They might be mere outhouses with lean-to roofs, as in hand file-cutting at Sheffield: or ordinary small rooms in buildings of several storeys, as in many tailoring workshops, &c.: or large rooms occupying the whole of one storey, and either communicating freely by inside stairs or lifts with rooms above and below, or isolated from them: or still larger rooms occupying the whole of a high building, and with galleries running round inside: or large sheds lighted from above. The roofs and walls also varied greatly as regards their permeability to air.

Sometimes there were no evident openings for ventilation, although we occasionally found that in such rooms the actual ventilation was fairly good, on account of the permeability of the roof and walls: often there were open windows, and often other ventilating openings of various kinds, including open stairs, lift-shafts, and gratings to the rooms above or below. In the larger rooms ventilation by fans was found to be common, while in the smallest rooms open fireplaces often enough served as the chief means of ventilation during the colder weather.

The means of heating employed also varied greatly. In the larger rooms heating by steam-pipes, carried either near the floor, or overhead, was the commonest method. In smaller rooms gas-stoves usually provided with flues, ordinary coal-stoves, and open fires were employed. In many rooms, however, the heating arrangements were inadequate in cold weather, and the objectionable method of attempting to heat the room by lighting the ordinary gas-jets was often resorted to. Sometimes there was no other method of heating. Warming the incoming air was seldom resorted to, unless the air was artificially humidified, as in many cotton-cloth weaving sheds. In employments not of a sedentary nature heating arrangements were often not provided because they were not required. In other employments heat from the machines used was sufficient to warm the room. In certain employments, such as cotton-spinning, the nature of the work necessitated a very high temperature, which was maintained by steam-pipes and heat from the machines. By the Factory Act it is provided that "in every factory or workshop adequate means must be taken for securing and maintaining a reasonable temperature in each room in which any person is employed, but the means so taken must not interfere with the purity of the air of any room in which any person is employed." In sedentary occupations a temperature of not less than about 60° F. (15·5° C.) appears to be necessary for comfort.

As a general rule factories and workshops are not nearly so densely occupied as many ordinary public buildings, such as churches, theatres, schools, halls for public meetings, &c. This is due chiefly to the fact that considerable floor-space is needed in almost all employments, and partly also to the provision in the Factory Act that there shall be a minimum of 250 cubic feet of space to each person employed in any room, and 400 cubic feet during work overtime. The average cubic space per person in the rooms which we examined was 1875, or if rooms with over 5000 cubic feet per person be excluded, 925. In elementary schools Carnelley, Haldane, and Anderson[1] found an average of 168

[1] *Loc. cit.*

cubic feet; and in many public buildings the space per person is no greater. The relatively greater cubic space in factories and workshops renders their proper ventilation not so difficult as in the case of public buildings. Ventilation by natural means is usually more practicable, as there is not the same necessity for warming the incoming air in order to prevent unpleasant draughts, relatively gentle air-currents being sufficient.

Carbonic Acid in Outside Air.

Before discussing the average results of the analyses it is necessary to refer shortly to the variations in the carbonic acid of outside air. In the air of the open country the proportion of carbonic acid averages almost exactly 3·0 volumes per 10,000. The very careful and complete series of determinations made in France by Reiset[1] in 1872–80 gave an average for day and night of 2·96 volumes. He absorbed the carbonic acid with baryta water, and used 525 litres of air for each determination, of which there were 220. The following table shows the corrected results of a series of exact determinations by Miss E. S. Haldane and myself, made at Cloanden, Perthshire, in 1889–90, and not hitherto published. The method used was the gravimetric one of Haldane and Pembrey[2]. The samples were taken at 4 feet from the ground, and 76·7 litres of air were used for each determination.

		No. of analyses	Volumes of CO_2 per 10,000			
			Maximum	Minimum	Average	
April 1—Sept. 30	Day	29	3·11	2·58	2·88	2·98
	Night	23	3·55	2·82	3·08	
December—January	Day	6	3·12	2·93	2·99	3·00
	Night	5	3·06	2·94	3·01	

The older determinations by Pettenkofer's method gave results which varied considerably according to the particular manipulations employed, and were usually too high by about 0·5 volumes per 10,000, though occasionally also too low. The action of the baryta water on the glass bottles probably accounts, in part at least, for the errors.

[1] *Annales de Chimie et de Physique*, Vol. XXVI. 1882, p. 198.
[2] *Philosophical Magazine*, 1890, p. 306.

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The experiments of Angus Smith and others have shown that in English towns the proportion of carbonic acid in the outside air is sensibly greater than in the country. The most complete series of determinations is that of Dr Russell for London air at St Bartholomew's Hospital[1]. Excluding foggy days his averages were as follows.

	No. of Analyses	Volumes of CO_2 per 10,000		
		Maximum	Minimum	Average
April—September	92	4·8	3·0	3·81 } 4·01
October—March	40	6·4	3·2	4·22 }

The average of 29 determinations on foggy days was 7·2 volumes, the maximum being 14·1 volumes and the minimum 4·5 volumes.

The method used was that of Pettenkofer, so that probably the average results were about 0·5 volumes too high.

Russell's experiments show clearly that on foggy days in towns the proportion of carbonic acid in the air inside a building may be considerably raised in consequence of the vitiated state of the outside air.

Average Results of Analyses in Factories.

The general average of carbonic acid in the rooms which we examined was 10·1 volumes per 10,000 for analyses made during day-light or with electric lighting, and 17·6 during gas-light. It should be remarked, however, that very few analyses were made during summer weather, when ventilation is usually much more free, owing to the opening of windows: also that the rooms visited were chiefly those in which without due care the air would be liable to become considerably vitiated. The average for *all* factories and workshops would doubtless be lower than the figures just given.

As the great majority of the rooms examined were in towns, with a probable average proportion of about 3·5 volumes per 10,000 in the outside air, the average excess of carbonic acid in the rooms examined was about 6·6 volumes with no gas burning and 14·1 volumes with gas burning. The carbonic acid in the outside air was actually determined in all cases where there was any mist or fog. The maximum proportion found was 6·5 volumes (during a fog in the City, London), and

[1] *St Bartholomew's Hospital Reports*, Vol. xx.

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the average for such days and nights was 5·0 volumes, and on other days 3·4 volumes. The results of each analysis, both of outside and inside air, are contained in Appendix I. of the Committee's Report. All the analyses were made by the rapid method already referred to, which has been found to give an average result of 3·0 volumes for unvitiated outside air.

The maximum proportion of carbonic acid found by day was 46·2 volumes. This was in a very tightly-closed spinning room, with an average cubic space per person of 10,169 cubic feet. Gas was burnt in this room in the morning and evening, and the carbonic acid was undoubtedly mostly produced by combustion of gas many hours previously. The temperature was 33·3° (92° F.).

The average proportion of carbonic acid found is less than that in many public buildings, and evidently the air of factories and workshops generally is not relatively speaking so much vitiated by overcrowding as is sometimes supposed. To make only one comparison, the average proportion of carbonic acid in elementary schools (in Dundee) was found by Carnelley, Haldane, and Anderson to be 18·6 volumes per 10,000 with natural ventilation, and 12·3 volumes with the very imperfect mechanical ventilation employed at the time (1886) in some of the schools investigated. As a general rule employers, and particularly the more energetic and prosperous ones, are anxious to do all in their power to secure satisfactory ventilation. Bad ventilation is frequently due to objections on the part of a few of the employees, or to failure on the part of architects or others to carry out the intentions of employers. In a good many cases, however, far too much reliance is placed upon the existence of a large air-space per person employed.

Only about 40 determinations were made of micro-organisms. The average number per litre in rooms where there was no undue disturbance of dusty material (as occurs, for instance, in the preparation of cotton, jute, hemp, &c. for spinning) was 8·0 bacteria and 2·2 moulds, or 10·2 micro-organisms in all. The determinations from which this average is calculated were made chiefly in printers', bookbinders', tailors', and milliners' workrooms during the winter months, and indicate a fairly satisfactory standard of cleanliness. The average compares very favourably with the averages of 152 in elementary schools in Dundee[1], 76 in country board-schools in Scotland[2], 60 for

[1] Carnelley, Haldane, and Anderson, *loc. cit.*

[2] Carnelley and Foggie, *Journ. of Pathol. and Bacteriol.* Vol. II. p. 157.

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one-roomed dwellings in Dundee[1], 46 for two-roomed dwellings[1], and 9 for the better classes of dwelling[1]. No determinations were made by the Committee of micro-organisms in outside air, but in Dundee the average in the winter months was 0·8 per litre[1]. In summer, as shown by Frankland[2] and others, the numbers in outside air in towns are far higher. By the first section of the Factory Act it is enacted that "every factory must be kept in a cleanly state."

In factories where much organic dust passes into the air from machines, &c., the number of micro-organisms in the air may of course be very great. Thus in a rope factory close to a dusty machine we found as many as 850 per litre. There was no reason to suspect, however, that any of the organisms present were pathogenic.

Influence of Combustion of Gas.

Were there no other products of the combustion of coal-gas except carbonic acid and moisture, the changes produced in the air of rooms by its combustion would be of little practical importance apart from the rise of temperature. Coal-gas, however, always contains a little sulphur—chiefly in the form of carbon bisulphide. This is burnt to sulphuric acid, which is apparently the cause of the characteristic oppressiveness of air much vitiated by the burning of gas. Air vitiated by the combustion of gas to the extent of 20 volumes per 10,000 begins to feel distinctly oppressive, even with well-purified gas. With good and clean paraffin lamps burning in a closed room I was unable to observe any similar effect even when the proportion of carbonic had risen as high as 75 volumes per 10,000.

The quantity of sulphur present in gas varies considerably in different towns, according as the gas is or is not thoroughly purified. In London, where the purification is good, and there is a legal limit to the amount of sulphur permitted, about 0·75 gramme of sulphur per 100 cubic feet of gas is usually present; but in some of even the larger English towns the amount of sulphur present is a good deal higher, so that air vitiated by combustion of gas is correspondingly more unpleasant.

A common gas-jet, such as is usually met with at present in English factories and workshops, consumes from 5 to 10 cubic feet of gas per hour; and this amount of ordinary English gas produces in burning from $2\frac{1}{2}$ to

[1] Carnelley, Haldane, and Anderson, *loc. cit.*

[2] *Loc. cit.*

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5 cubic feet of carbonic acid. The mean of two analyses which I made of ordinary gas of 16 to 17 candle-power gave the following results per volume of gas burnt.

Carbonic acid formed ...	0·54	volume.
Aqueous vapour „ ...	1·19	„
Oxygen consumed ...	1·14	„

As the aqueous vapour does not under ordinary circumstances condense, the products of combustion are, even after cooling, lighter than air: for although the carbonic acid is about 37 % heavier than the oxygen which it replaces, the aqueous vapour is about 42 % lighter, and present in much greater volume. From this circumstance and the fact that the heated products of combustion ascend in a concentrated stream towards the roof, and that gas-jets are usually at a height of six feet or more, the circulation of vitiated air from gas-jets is to a large extent above the breathing level. The following analyses of the air of a room of 5700 cubic feet and 11½ feet high illustrate this point. All openings were closed and only one person was present. Three No. 4 union burners were lit, passing in all about 15 cubic feet of gas per hour. The gas-jets were at a height of 6½ feet from the floor, on the walls at opposite sides of the room. The samples were taken at the centre of the room.

	Volumes of CO_2 per 10,000		
	At 1 foot from floor	At 4 feet from floor	At 1 foot from roof
Before gas lit		2·9	
13 minutes after gas lit			13·8
18 „ „ „		4·8	
24 „ „ „	7·5		
30 „ „ „			20·2
36 „ „ „		9·0	
44 „ „ „	12·7		
53 „ „ „		13·9	
59 „ „ „			27·7
64 „ „ „	16·5		
68 „ „ „		17·4	
90 „ „ „			34·3
96 „ „ „		19·4	
102 „ „ „	19·6		
140 „ „ „			39·0
144 „ „ „		25·8	
148 „ „ „	24·8		

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The temperature at the beginning of the experiment was 12·5°, and at the end 15·4° at 4 feet from the floor, and 19·4° at 1 foot from the roof. The outside temperature was 9°.

With the products of respiration the distribution in a room is different. In expired air about 4 % of oxygen is replaced by about 3½ % of carbonic acid, and about 4 to 5 % of aqueous vapour is added. This mixture, when diluted and cooled, is very nearly as heavy as pure air: it is not nearly so much heated as the products of combustion; and convection currents due to warming of the air by the bodies of the persons present cause it to mix very completely with the air of the room unless it can escape promptly at the roof. This is illustrated by the following experiment made in a room 11 feet high, and with 3070 cubic feet capacity. Four persons were present, and all openings closed. The samples were taken at the centre of the room.

	Volumes of CO_2 per 10,000	
	At 4 feet from floor	At roof
Before experiment	2·8	
After 20 minutes	5·5	4·7
„ 70 „	10·9	11·5
„ 90 „	12·8	12·1
„ 110 „	16·4	16·4
„ 125 „	16·6	16·7
Average	10·37	10·23

In calculating the probable effect of combustion of gas on the purity of the air of a room it is evidently necessary to consider to what extent the arrangements for ventilation permit the heated and vitiated air from gas-jets to escape without mixing with the air at the breathing level. The experiment already quoted shows that in high rooms the air at the breathing level will usually be less vitiated by gas than in low rooms of equal cubic space. Where, however, the incoming air is introduced at a high level, or where driving-belts for machinery are constantly mixing the air at different levels, as in weaving-sheds, there is much more complete mixture than in other rooms, so that more fresh air is needed to keep the air at the breathing level reasonably pure. In an ordinary weaving-shed, ventilated through the roof, we found that the excess of carbonic acid rose to four times as much when the gas was lit. There were $2\frac{1}{3}$ small (No. 4) gas-jets per person present. The details of this observation are given later.

The relative increase of air-vitiation in any given work-room after gas is lit depends also upon the proportion of gas-jets to persons present. This proportion was found to differ very greatly in different work-rooms. Where there is much machinery or floor-space to each worker the number of gas-jets may greatly exceed the number of workers. Thus in spinning-rooms there are often three or four gas-jets to each person: consequently the production of carbonic acid after gas is lit may rise to ten or twelve times what it was during day-light. On the other hand, in the more crowded rooms where sewing, &c. are carried on there may only be one jet to two or three persons, so that the production of carbonic acid is only about doubled after gas is lit, and the actual proportion of carbonic acid in the air at the breathing level may be scarcely at all increased if the vitiated air has free means of escape above.

Much may be done towards diminishing the vitiation of air through combustion of gas by avoiding wasteful methods of burning it. The following table (p. 428) shows the results of a series of experiments which I made on the light obtained for a given consumption of gas with various forms of ordinary burners in common use. London gas was used, averaging at the time about 16·5 candle-power—*i.e.* giving a light of 16·5 standard English candles when burnt at a rate of 5·0 cubic feet (measured at 60° F. and 30·0 inches barometric pressure) per hour through the standard "London Argand" burner prescribed by the Metropolitan Gas Referees. The standard light used in the experiments was the official ten-candle pentane lamp of the Metropolitan Gas Referees. The results with incandescent mantles at the end of the table are quoted from a Report published by the German Association of Gas and Water Engineers (*Journal of Gas-lighting*, April 16, 1901).

It will be seen from this table how greatly the amount of light obtained per cubic foot of gas burnt varies according to the method of consumption. The light was 48 times as great with the best as with the worst method. With ordinary burners the best result is evidently obtained from those with the larger sizes of opening, and with the gas issuing gently. Thus, to take an extreme instance, the light from a No. 0 burner at full pressure was increased nine times when a No. 7 (so-called "economiser") was slipped over it, so that the gas which passed at high velocity from the No. 0 burner underneath issued at low velocity from the much wider opening of the No. 7 burner above. The

Description of Burner	Pressure in inches of water between tap and burner	Consumption of gas in cubic feet per hour	Light in candles	Light in candles per cubic foot of gas burnt
Standard "London Argand"	—	4·86	16·0	3·29
"Union" or "fish-tail" No. 8	1·7* 1·4 0·8 0·4 0·2†	12·6 11·2 8·2 5·6 3·15	22·6 24·0 23·7 17·5 9·1	1·79 2·14 2·87 3·12 2·89
"Union" No. 6	1·8* 1·2 0·8 0·4	10·0 8·1 6·25 4·15	12·8 15·7 14·3 10·0	1·28 1·94 2·29 2·41
"Union" No. 4	2·0 1·7 1·2 0·8 0·4	9·4 8·3 6·7 5·1 3·6	6·1 8·9 9·4 8·4 6·8	0·65 1·67 1·40 1·65 1·89
"Union" No. 2	1·8 1·2 0·8 0·4 0·2†	5·5 4·5 3·8 2·4 1·45	3·45 3·45 3·5 2·8 1·9	0·63 0·77 0·92 1·17 1·34
"Union" No. 0	1·9 1·2 0·8 0·4 0·2†	4·5 3·5 2·7 1·55 0·97	1·6 1·7 1·6 1·3 0·88	0·36 0·49 0·59 0·84 0·91
"Batswing economiser" No. 7, placed on "Union" No. 0	1·9 1·2 0·2†	4·5 3·5 0·97	14·7 11·0 2·1	3·27 2·97 2·16
"Union economiser" No. 6, placed on "Union" No. 2	2·3 1·8	5·9 5·25	13·9 12·4	2·36 2·36
Common iron "Batswing," no number (irregular flame)	0·6* 0·4 0·3 0·2 0·15	16·0 13·0 10·5 7·6 5·5	37·3 37·7 34·2 25·3 17·8	2·33 2·90 3·26 3·33 3·24
"Batswing" No. 7	1·1 0·7 0·4	12·0 9·5 6·1	26·2 22·9 18·2	2·18 2·41 2·98
Cone-top burner, no number	1·8 1·2 0·5†	6·8 4·55 1·8	21·6 14·5 4·55	3·18 3·19 2·53
Cone-top governor burner	2·0 1·0	4·95 4·8	16·05 15·65	3·24 3·26
Average of incandescent mantles { After 1 hour's use " 24 " " 100 " " 300 " " 600 "	— — — — —	4·25 4·25 4·25 4·25 4·25	73·9 70·3 62·2 56·4 53·8	17·4 16·5 14·6 13·3 12·7

* Flaring. † Small flame.

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difficulty in securing a satisfactory result at all times with a given burner arises largely from the fact that the pressure in the main pipes is often allowed to fall very low. Where this is not the case a good result can be secured by using suitable burners and placing a pressure-governor on the supply pipe, or by using governed burners. In London there is a legal minimum (1 inch of water) to the pressure permitted in the main pipes.

The table shows clearly the great advantages of incandescent mantles. Their much more general employment in factories and workshops is very desirable, with a view to avoiding excessive vitiation of the air and at the same time obtaining a good and perfectly steady light.

By the use of the incandescent electric light all the inconveniences due to air-vitiation and heat from gas-jets can be avoided, though the extra expense as compared with incandescent gas-light is usually considerable. The arc electric light, so shaded that only reflected light falls on employees and machines, is sometimes used with great advantage.

The most wasteful methods of burning gas are still very commonly used in English factories and workshops, in spite of the greater expense and increased vitiation of the air; and there is much room for improvement in this respect.

Influence of Cubic Space per Person.

In the following table our observations are arranged so as to show the relations between the air-space per person and the proportions of carbonic acid in the air. Where, as was often the case, several analyses had been made of the air in one room the average for day-light or gas-light in that room has alone been counted in constructing the table, so that the general average may be as fair as possible.

Cubic feet per person		Under 300	300 to 400	400 to 600	600 to 1000	1000 to 1500	1500 to 2000	2000 to 5000	Over 5000
Average cubic feet per person		233	339	496	760	1227	1689	2906	9404
Volumes of CO_2 per 10,000	Day-light or electric light	11·4	10·6	9·7	10·2	9·2	9·0	7·1	12·8
	Gas-light or lamp-light	20·1	13·6	14·0	13·8	17·4	19·0	17·8	26·3
No. of rooms examined	Day-light or electric light	36	33	28	27	27	25	24	25
	Gas-light or lamp-light	14	8	15	18	14	9	5	12

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It will be seen from the table that there was no general decrease in the carbonic acid with increase in the cubic space per person; and indeed the highest results were obtained, curiously enough, in the rooms with most space per person. This was evidently due partly to a large number of these rooms being spinning-rooms, which are commonly kept tightly closed in order to prevent cooling. In gas-lit rooms there is on the whole a marked relative increase in carbonic acid in rooms with a large cubic space per person. This is explained by the fact that in such rooms the proportion of gas-jets to persons is usually much greater than in rooms with a small cubic space per person. It is quite clear from the table that a large cubic space per person affords no guarantee for purity of the air. In factories and workshops, where rooms are always continuously occupied for some hours, foul air is about as often met with in sparsely occupied as in crowded rooms.

Influence of Time of Occupation.

In any occupied room a certain interval will elapse before the impurity of the air reaches an amount beyond which it does not further increase. The larger the air-space per person and the smaller the air-supply per person the longer will be this interval. In examining by chemical analysis the ventilation of a room it is frequently of importance to know whether the respiratory impurity of the air has already reached its probable maximum, or if not, how much higher the impurity is likely to increase.

In order to make calculations on these points it is first of all necessary to know the probable amount of carbonic acid given off per person and per hour in the room. In any particular person this amount varies considerably according to the amount of muscular work being done at the time. During great muscular work the amount may temporarily rise to ten times as much as during rest. The average for the 24 hours can best be calculated from the average daily consumption of food, which is pretty accurately known, and corresponds in the case of an adult man to an energy-value of about 3500 calories. Allowing for non-absorption of a small part of the food, and for the fact that the greater part of it consists of carbohydrate, the average production of carbonic acid for an adult man must be about 22 cubic feet per day or 0·9 cubic foot per hour. During complete rest only about 0·6 cubic foot per hour is given off, however: hence during the hours of activity about 1·1 cubic foot per hour is probably produced. A woman produces about

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a fifth less than a man. In a factory about 1 cubic foot per hour may therefore be taken as a probable average quantity per person, though a higher estimate would be needed in cases where there is a good deal of muscular exertion.

The following table, for the calculation of which we are indebted to Mr P. J. Kirkby, Fellow of New College, Oxford, furnishes an easy means of estimating the probable maximum to which the proportion of carbonic acid in the air of a room will ultimately rise, and the rate of ventilation, assuming the latter to remain constant and the mixture of the air to be fairly complete.

$\frac{E}{E_0}$	$\frac{T}{t}$	$\frac{E}{E_0}$	$\frac{T}{t}$	$\frac{E}{E_0}$	$\frac{T}{t}$
·95	10	·72	1·43	·50	·62
·93	7·5	·69	1·25	·48	·59
·90	5	·66	1·1	·45	·53
·87	3·3	·63	1·0	·43	·50
·85	3·0	·61	·91	·40	·45
·82	2·5	·58	·83	·37	·40
·79	2·0	·56	·77	·35	·37
·77	1·8	·54	·71	·30	·31
·75	1·67	·52	·67	·25	·25

To use the table it is first necessary to calculate the excess of volumes of carbonic acid per 10,000 of air which would have been present with no ventilation at all. As each person produces about a cubic foot of carbonic acid per hour this number (E_0) is found by multiplying the persons present by the time in hours of occupation, and dividing the result by the cubic feet of air-space in the room divided by 10,000. Thus if the room has a capacity of 50,000 cubic feet, and 150 persons have been present for half-an-hour

$$E_0 \text{ will be} = \frac{150 \times 0{\cdot}5}{\frac{50{,}000}{10{,}000}} = 15.$$

The ratio of the observed excess (E) to E_0 is then calculated. Thus if 9·5 volumes have been found in the air E may be taken as $9{\cdot}5 - 3{\cdot}5 = 6$, if the room is in a large town; and the ratio $\frac{E}{E_0}$ will be $\frac{6}{15} = 0{\cdot}4$. The maximum to which E will subsequently rise is then found by multiplying E_0 by the number standing opposite to the value of $\frac{E}{E_0}$ in the second

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column of the table. As in the supposed case this value is 0·4, and the number opposite is 0·45, the required maximum value of E is $15 \times 0{\cdot}45 = 6{\cdot}7$, so that the carbonic acid will ultimately rise to $6{\cdot}7 + 3{\cdot}5 = 10{\cdot}2$ volumes per 10,000.

If the ratio $\frac{E}{E_0}$ is less than the least number in the first column, the corresponding number in the second column is the same, as the two columns have reached an equality. In this case the maximum proportion of carbonic has been reached, and there will be no further vitiation. Practically speaking, if the ratio $\frac{E}{E_0}$ is less than a third the maximum has been reached: if the ratio $\frac{E}{E_0}$ is greater than unity it is pretty certain that the air of the room was not pure to start with or that gas has been burning, or impure air entering the room.

The numbers in the second column of the table are in each case the ratio of the time (T) required for the entry of a volume of air sufficient to fill the room to the time (t) during which the room has been occupied. It is thus easy to calculate the value of T; and the cubic capacity of the room divided by T gives the number of cubic feet of air per hour being introduced. Thus in the above example, since $\frac{T}{t}$ was 0·45, and t was 0·5, $T = 0{\cdot}5 \times 0{\cdot}45 = 0{\cdot}225$, and the ventilation per hour was $\frac{50{,}000}{0{\cdot}225} = 222{,}000$ cubic feet, or $\frac{220{,}000}{150} = 1480$ cubic feet per person.

It must always be borne in mind that the temperature of a room frequently increases up to a certain point with the duration of occupation, and that this may increase the rate of ventilation, so that the excess of carbonic acid will not actually rise so high as the calculated excess. The accuracy of the calculation is also limited by the fact that the production of carbonic acid per person may be somewhat greater or less than one cubic foot per hour, according to the nature of the work, &c.

For practical purposes the following abbreviated table will be found useful.

When the value of $\frac{E_0}{E}$ is	3 or more	2	1·75	1·5	1·25
The probable maximum future excess will be $E \times$	1	1·24	1·4	1·7	2·7

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The probable number of cubic feet of fresh air per person and per hour is obtained by dividing 10,000 by the value obtained for the maximum future excess.

In taking samples of air we, so far as possible, selected times at which the impurity of the air would have reached its maximum. Hence it is possible to calculate the probable average air supply per person and the time required for the air of the room to be changed (*i.e.* for a volume of air equal to that of the room to enter) in the various rooms examined. The following table gives the average results for rooms of different sizes, the outside air being assumed to contain 3·5 volumes per 10,000 of CO_2.

Cubic feet per person	Under 300	300 to 400	400 to 600	600 to 1000	1000 to 1500	1500 to 2000	2000 to 5000	Over 5000
Average cubic feet per person	233	339	496	760	1227	1689	2906	9404
Volumes of CO_2 per 10,000 day-light or electric light	11·4	10·6	9·7	10·2	9·2	9·0	7·1	12·8
Air supply per person in cubic feet per hour	1266	1408	1613	1493	1754	1818	2777	1075
Time required for air of room to be changed, in hours	0·18	0·24	0·31	0·51	0·70	0·93	1·05	8·7*

* Minimum figure.

The most striking fact brought out by this table is the rapidity with which the air was changed in the more crowded, as compared with the less crowded rooms. In the rooms with less than 1000 cubic feet of air-space per person the air was on an average changed in from 0·18 to 0·51 hours, so that as explained above, the air would reach its maximum impurity in from 0·54 to 1·53 hours. In the rooms (mostly spinning-rooms) with over 5000 cubic feet per person, on the other hand, the air-exchange was so slow that the maximum impurity could not have been reached during the hours of occupation, and the air could not have been pure on starting work again next morning. That this was actually the case we ascertained by special observations in one or two cases. Thus in two spinning-rooms with an average of 9840 cubic feet per person we found that after 4½ hours of occupation the average proportion of CO_2 was 10·6 volumes, and 5 hours later just before work stopped, 16·7 volumes. In two other similar spinning-rooms visited at 6·30 a.m. just as work commenced, the average proportion of CO_2 was 7·9 volumes. It was also found that in rooms of this

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class when gas was burnt in the morning and evening the proportion of CO_2 remained very high all day. Thus in one room with 10,170 cubic feet of air-space per person 46·2 volumes were found about six hours after gas had been extinguished, whereas in the same room under similar conditions, but at a time of year when no gas was used, only 16·5 volumes were found at the end of the day's work.

Circumstances affecting Natural Ventilation.

Most of the rooms examined by us were ventilated by "natural" means—*i.e.* without the use of fans or other artificial methods of producing a current of air. In many of the rooms there were no special openings for ventilation. The rate of natural ventilation must evidently depend on a number of variable factors such as the amount of wind, the difference of temperature between inside and outside, the permeability of the walls and roof, the existence of various openings, &c. In all rooms a certain amount of exchange of air occurs through the walls, roof, floor, and various chinks, as was originally proved experimentally by Pettenkofer.

Since it was important to obtain some definite data as to the amount of air which under ordinary circumstances passes through various kinds of rooms unprovided with special means of ventilation, I made a number of special experiments on this point. The method usually adopted was to leave a certain number of paraffin candles burning at even intervals over the floor of the room. From the weight of paraffin burnt in a given time the volume of CO_2 produced (which was found by experiment to be ·058 cubic foot at 15·5° and 760 mm. pressure per gramme of candle burnt) could be estimated, so that from the excess of carbonic acid in the room above that of the outside air the volume of air entering the room could easily be calculated from the table already given. The percentage of carbonic acid from the candles was in some experiments somewhat higher nearer the roof or on one side, but the calculations are based on the analyses of samples taken at the centre of the floor and at the breathing level. In the experiments on the first room the ventilating effects of an open fire-place are also shown. In all cases the rooms and surrounding rooms were thoroughly ventilated before starting, and since the buildings were practically in the country the proportion of carbonic acid could safely be assumed to be as nearly as possible 3·0 volumes per 10,000 in the room before starting and in the outside air. If any person was present during the experiment the carbonic acid

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produced by him was allowed for. The analyses were by the method referred to above. The details of the experiments are stated in Appendix II. of the Committee's Report. The results are summarised in the following table (pp. 436 and 437).

These experiments, along with our observations in factories and workshops, throw a good deal of light on various circumstances which affect natural ventilation. Taking first the case of rooms with no fire-places or other openings, it will be seen that in the two small rooms (A and C) of 1100 and 1400 cubic feet, with boarded floors above and below, and no appreciable wind, the air was changed in from 2 to 3 hours, while in the larger room of the same character (D, 5600 cubic feet) the rate of change was once in 3 to 5 hours. It is evident that, the form and general construction being the same, the larger a room the more slowly will the air in it be changed by penetration of air through the walls, &c.: for the extent of wall, roof, and floor surface does not increase in the same proportion as the cubic capacity. The surface increases as the square, and the capacity as the cube, of any corresponding diameter, for rooms of the same shape. Thus an increase of 8 times in the capacity will correspond to an increase of only 4 times in the surface. Very large rooms, when unprovided with openings for ventilation, may thus contain foul air, although the air-space per person is very large. Many striking examples of this were met with in factories. Thus in a spinning-room of 91,500 cubic feet, containing only 9 persons as sources of vitiation, the carbonic acid during the day was found to rise as high as 16·5 volumes per 10,000, and this in spite of the fact that the temperature was extremely high (33°), which would naturally favour the exchange of air. The rate of change of air was apparently not more than about once in 24 hours. The apparently anomalous fact that we found the carbonic acid on the whole highest with a very large air-space per person, even with no gas burning, is to a great extent explained by the fact that the rooms with a very large air-space per person were relatively very large.

Structural differences, such as varying permeability of roof or extent of outside wall, may greatly affect natural ventilation. Thus in rooms B, F, G, and H, in which the construction favoured ventilation, the rate of ventilation with all openings closed, and no wind, was greater than would otherwise have been expected from their cubic capacity. The influence of an easily permeable roof was very clearly shown in some of our observations on weaving-sheds. In most weaving-sheds the roof is fairly permeable, so that in spite of the very large cubic capacity the

30—2

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Description of Room	Duration of experiment in hours	Temperature		Hours required for a vol. of air equal to that of the room to enter	Remarks
		Inside	Outside		
Room A. Capacity 1390 cubic feet, 9·3 feet high, bedroom on first-floor, fire-place and one window, one outside wall of brick, walls and ceiling papered	11·6	17·2° to 17·8°	16·7° to 10·6°	2·1 to 3·4	Flap of fire-place closed. Breeze scarcely perceptible
Same room	12·5	17·9° to 18·3°	14·5° to 11·0°	1·3 to 1·8	Strong wind throughout experiment. Flap closed
				0·6 to 0·7	Flap open
Same room	14·0	18·3° to 17·4°	15·8° to 10·2°	0·9 to 1·3	Flap closed. Moderate breeze
				1·7 to 2·4	Breeze very slight
				0·7 to 0·8	Lower sash of window raised 7 inches
Same room	5·6	16°	14·2°	0·8 to 1·1	Flap open. Very slight breeze
Same room	3·7	16·7°	9·0°	0·9 to 1·0	Flap open. Very slight breeze
Same room	3·6	19·4° to 18·8°	13·5° to 13·8°	0·2 to 0·4	Fire burning in grate. Slight breeze
Room B. Attic of irregular shape, 786 cubic feet, one window, walls papered	3·2	17·8°	11·0° to 10·5°	1·2 to 1·8	Wind imperceptible
Room C. 1100 cubic feet, 11·5 feet high and nearly square, laboratory room on ground-floor, one window, one outside wall of sandstone, one inside wall of sandstone, and two of wood and plaster, walls not papered	9·2	13·0°	8·0°	1·5 to 1·6	Slight breeze
Same room	9·3	13·9°	4·5°	2·4	No breeze
Same room	8·0	13·5° to 13·6°	11·5° to 9·0°	1·3 to 1·5	Wind scarcely perceptible. A fixed ventilator opened at roof, opening about 24 sq. inches
Same room	4·0	17·2°	14·5°	0·25 to 0·30	Strong wind throughout experiment. Ventilator open

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Description of Room	Duration of experiment in hours	Temperature		Hours required for a vol. of air equal to that of the room to enter	Remarks
		Inside	Outside		
Room D. 5600 cubic feet, 11·5 feet high, and nearly square, laboratory room on ground-floor, two double windows, one outside wall of sandstone, one inside wall of sandstone, one of brick and one of wood and plaster, no fire-place, no paper on walls	9·25	13·8° to 14·0°	11·8° to 9·2°	4·1 to 5·2	Wind scarcely perceptible. Simultaneous with third exp. on Room C
Same room	11·2	13·0°	5·0°	3·0 to 3·4	Slight breeze
Same room	3·8	17·8°	14·5°	1·4 to 1·9	Strong wind. Simultaneous with fourth exp. on Room C
Room E. 18,800 cubic feet, 11·5 feet high and 70 × 24 feet, a long laboratory room on ground-floor, 12 windows and 4 doors, 70 % of wall is to outside and of sandstone, otherwise like room D	7·2	13·5°	11·8° to 9·2°	1·8 to 2·5	Wind scarcely perceptible. Simultaneous with first exp. on Room D
Same room	4·2	17·5°	14·5°	1·5 to 2·0	Strong wind. Simultaneous with third exp. on Room C
Room F. 13,300 cubic feet, 15 feet high and nearly square, ground-floor, one large open fire-place and two doors, two outside walls of stone	6·7	16·8° to 17·8°	15·6° to 14·0°	1·9 to 2·9	Gentle breeze. Chimney open and considerable draught up it. Simultaneous with first exp. on Room G
Room G. 75,000 cubic feet, 30 feet high in centre, stone walls and sloping ceiled roof with skylights, ventilators closed. Town-hall of Auchterarder	8·5	15·5° to 17·0°	14·4° to 12·2°	2·0 to 2·4	Gentle easterly breeze. Roof probably easily permeable to air
Same room	6·6	16·0° to 18·5°	16·7° to 17·3°	2·5 to 3·5	Wind scarcely perceptible
Room H. 72,000 cubic feet and 28 feet high in centre, side windows, ventilated by openings in roof measuring about 46 square feet in all, and communicating with loft below slates. Free Church, Auchterarder	5·5	11·7° to 16·0°	12·7° to 13·8°	2·2 to 3·3	Gentle breeze

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exchange of air is usually considerable, even when all ventilators are closed. In some sheds, for instance, we found that with all, or nearly all, ventilators closed, and about 1500 to 2500 cubic feet per person, the carbonic acid during the day only rose to 6 or 7 volumes per 10,000. In one shed, however, the roof, instead of being of the usual saw-back construction, was covered with a sheet of water for coolness, with skylights projecting through. The roof was thus exceptionally air-tight. Observations made in this shed at a time of year when all ventilators were kept closed gave the following results. The shed was about 12 feet high, with a capacity of 388,800 cubic feet, and 1620 cubic feet per person present.

			Vols. of CO_2 per 10,000
10.40	a.m.	Centre of shed	24·4
10.45	,,	N.W. corner	24·8
10.50	,,	S.W. ,,	25·2
11.15	,,	N.E. ,,	25·6
11.30	,,	S.E. ,,	25·6
5.0	p.m.	N.E. ,,	30·8
5.10	,,	S.W. ,,	31·2
5.15	,,	S.E. ,,	33·0
5.30	,,	Centre	33·0

These results show a rate of ventilation far lower than in any other weaving-shed which we examined.

The influence of an open chimney, with or without a fire burning in it, is very distinct in the experiments on room A. A bright fire increased the ventilation of room A as much as ten times, and the mere opening of the flap of the grate doubled the ventilation. The influence of opening a window in room A and of a small ventilator in room C is also shown.

The influence of wind in increasing natural ventilation is shown very distinctly. In rooms A, C, and D the ventilation was increased by from two to six times by a strong wind.

Difference of temperature between inside and outside must affect the exchange of air, particularly if the roof is easily permeable, or contains openings, and when the whole of a high building is heated. The effects of temperature were not, however, clearly apparent in the candle experiments; and it must be remembered that the driving pressure due to ordinary differences of temperature is slight as compared to that due to even a gentle breeze. In the following observations, made in a large and well-ventilated weaving-shed at

Auchterarder, the effects of temperature are clearly seen. The shed was of 472,000 cubic feet capacity, and about 16 feet high, with the usual saw-back roof. There were 72 10-inch cylindrical ventilating pipes in the roof, all open, and the air-space per person was 2,350 cubic feet. Work began at 9 a.m. During the dinner-hour (1 to 2 p.m.) about half the employees remained in the shed. There was an easterly breeze during the observations. An analysis of the outside air gave 2·8 volumes of CO_2.

	Temperature		Volumes of CO_2 per 10,000
	Inside	Outside	
10.8 a.m. Centre of shed	12·2°	11·7°	5·3
10.40 " " "	13·8°	12·6°	6·2
11.40 " " "			7·3
12.20 p.m. " "	15·5°		6·6, 6·8
12.50 " " "	16·3°	15·3°	6·8
1.40 " " "			6·4
2.0 " " "	18·2°		4·6, 4·4
3.55 " " "	22·6°	13·8°	3·7, 4·2
12.35 p.m. West side of shed	15·5°		7·9
1.47 " " "	16·3°		7·0
4.10 " " "	22·6°	13·8°	4·0
12.47 p.m. East side of shed	15·5°		5·0
1.55 " " "	16·3°		4·6
4.17 " " "	23·7°	13·8°	2·7

During the afternoon the inside temperature rose rapidly, in consequence, chiefly, of the sun shining in through the windows, which faced west. It will be seen that as the temperature rose the excess of carbonic acid in the air gradually fell to about a fourth of what it had been in the morning. An interesting point also shown by the analyses is that the air was much less vitiated on the east than on the west side of the shed. This was almost certainly due to the easterly breeze.

The observations in this shed were repeated in winter, when gas was being used in the evening, and all but nine of the ventilators were closed. There was 2560 cubic feet of air-space per person. The shed was heated by steam-pipes. The gas-jets (429 No. 4 Bray's burners) were lit between 3.45 and 4 p.m. The results were as follows.

	Temperature Inside	Temperature Outside	Volumes of CO_2 per 10,000
10.0 a.m. Centre of shed			5·5
10.38 ,, ,, ,,	11·0°	3·5°	6·0
11.18 ,, ,, ,,	12·0°		6·0
2.20 p.m. ,, ,,	13·4°		4·8
3.35 ,, ,, ,,		5·5°	6·0
4.35 ,, ,, ,, Gas lit			15·8
4.45 ,, ,, ,, ,,			14·8
5.10 ,, ,, ,, ,,			14·6
10.30 a.m. East side of shed	11·0°	3·5°	5·9
11.30 ,, ,, ,,			6·2
3.30 p.m. ,, ,,	15°	5·5°	{5·9 5·7
4.50 ,, ,, ,, Gas lit			16·5
5.40 ,, ,, ,, ,,	17·5°		14·2
10.45 a.m. West side of shed			5·4
11.35 ,, ,, ,,	12·7°		5·7
2.35 p.m. ,, ,,	14·2°		{5·1 5·1
3.25 ,, ,, ,,		5·5°	6·0
5.0 ,, ,, ,, Gas lit			14·6
5.45 ,, ,, ,, ,,	17·5°		14·8

It will be seen that in spite of nearly all the ventilators being closed the CO_2 did not rise so high during day-light as during the forenoon in the previous observations, when the temperature inside was nearly equal to that outside. On this occasion there was a very slight westerly breeze, and the CO_2 was lowest on the west side of the shed. With the gas lit the excess of CO_2 increased four times, there being $2\frac{1}{3}$ gas-jets to each person present. An analysis of the outside air gave 2·8 volumes of CO_2. The roof of the shed was evidently very permeable to air.

When, as frequently happens in factories, &c. two or more floors are in free communication by stairs, lifts, or other openings, the vitiated air will pass upwards. We observed this in a number of cases. Thus in a printing establishment the air was found to contain 10·1 volumes of CO_2 per 10,000 in the basement and 24·5 volumes in the second-floor. The air entering the second-floor by the shaft of the lift contained 16·5 volumes. In another building the air entering from below by the stairs contained 13·8 volumes, and in the room itself 18·8 volumes. In another case the air of an empty upper room, with no persons or lights in it, contained 11 volumes. In another case the air entering

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from below by a grid contained 12·8 volumes, and the room itself 15·5 volumes. We noticed that as a general rule the air in basement or ground-floors is relatively pure. Basement and ground-floor rooms commonly act as intakes for whole buildings.

The openings for ventilation in factories and workshops are usually ordinary windows. For most rooms this seems to be the most practical arrangement; but the opening and closing of windows require constant attention, as their action is dependent on varying conditions of weather. In well-managed rooms a foreman or other person is responsible for having enough of windows open to keep the air fresh without causing inconvenience from cold or draughts, and for the proper regulation of the heating arrangements. The most suitable arrangement of windows varies greatly in different kinds of rooms. They should always, however, open at as high a point as possible, with a view both to avoidance of draughts, and to allowing the more ready escape of the heated air from lights and persons. Windows so arranged that the incoming air can be directed upwards are advantageous in winter, but should also be capable of being opened freely in summer. The free opening of windows in summer is an enormous advantage.

In very wide rooms, sheds, &c. special ventilators or shafts in the roof are often provided, and may be supplemented by Tobin tubes or other inlet openings. We frequently observed that these ventilators were either totally insufficient in size, or had been blocked up in cold or windy weather, and left in this condition. Often, too, the shafts are so obstructed by various contrivances as to be of very little use except in windy weather, when they are least needed, as natural ventilation through other channels is then at its maximum. Ventilators which are well designed with a view to avoidance of draughts in windy weather, or to utilisation of the effect of wind, are often quite insufficient to give the necessary quantity of air in still weather, so that unless windows are opened the ventilation may be very bad. Roughly speaking a greater velocity than about 200 feet per minute or 12,000 feet per hour up a ventilating shaft can seldom be counted on in still weather, even with free inlets to the room. Hence to give a ventilation of 2000 cubic feet per hour, about one square foot of free outlet shaft would be needed for every six persons, together with corresponding inlet provision, if the ventilation depended entirely upon the ventilators.

In large and at the same time crowded rooms it is very difficult to provide adequate ventilation at all times except by the use of fans;

but observations such as those just quoted on the Scotch weaving-shed show that excellent results can be attained without mechanical ventilation even in very large rooms if there is no crowding. The difficulty in ventilating crowded rooms, if fairly large, without fans is well illustrated by the notoriously bad ventilation of elementary schools. The average proportion of carbonic acid in elementary schools during the winter months without fan ventilation was found to be 18·6 volumes, with an average of 168 cubic feet of air-space per child, and 15,450 cubic feet per room[1].

Ventilation by Fans.

Ventilation by fans has the great advantages that (1) practically unlimited quantities of air can be supplied; (2) the supply is completely under control, so that it can always be relied on; (3) the incoming air can be warmed, moistened, or filtered from soot; (4) dust and fumes can be removed at or near the points where they are given off. These advantages are so great as compared with the cost involved that where engine-power or electricity is available mechanical ventilation is now very largely used in factories, even in rooms which are not crowded.

A fan may be placed in either an inlet or an outlet for air, the best arrangement for any particular case depending on circumstances. If it is necessary to warm, filter, or moisten the incoming air the fan should, as a rule, be in an inlet, so that no untreated air can enter the room. On the other hand if the incoming air has not to be treated, the most convenient position is usually in an outlet placed high up. The incoming air then enters through the walls, roof, and various openings. The incoming air currents should be so directed and subdivided as to secure proper distribution of air, and reduce draught to a minimum. In rooms of great superficial area several fans are needed to secure proper distribution; and often a combination of inlet and outlet fans is advantageous. Where a fan is used for the removal of dust, steam, or fumes, which are escaping into the air and cannot be dealt with at their point of origin, the fan should be placed so as to draw off the vitiated air as directly as possible, and particularly not to draw it across the room. We found that mistakes as to this point are not infrequent. Proper heating arrangements must, of course, be combined with fan ventilation, whether or not the incoming air is heated. A short *résumé*

[1] Carnelley, Haldane, and Anderson, *Philosophical Transactions*, 1887, B, p. 79.

of details with regard to the power required, the arrangement of ducts, &c. will be found in Appendix II. of the Committee's Report.

Owing to the relatively large cubic space per person in factories (see above), and the fact that persons who are actively employed are less sensitive to draughts, fan-ventilation is more easy to arrange for in factories than in public buildings, and usually it is not necessary to warm the incoming air. Even in very crowded rooms, provided that the heating arrangements in winter are adequate, extraction fans placed high up in the walls or roof often answer very satisfactorily if the inlet openings are suitably distributed. For instance in a fully occupied room in a chocolate factory, with 153 persons present and 380 cubic feet of air-space per person, the average proportion of CO_2 was found to be only 4·9 volumes per 10,000. In a very overcrowded ordnance workshop, with 200 persons present, 19 gas-jets lit, and only 155 cubic feet of space per person the average proportion was 8·2 volumes. In both these instances the ventilation was by extraction fans in the walls.

Standards of Purity.

By the Factory Act of 1901 the Secretary of State is empowered to prescribe a standard of "sufficient ventilation" for any class of factories and workshops. No definite standard of purity has, however, hitherto been legally fixed, except in the case of cotton-cloth factories, in which artificially humidified air is employed. For these factories the Factory Act provides that in no part of the factory shall the proportion of carbonic acid in the air be greater than 9 volumes per 10,000. In practice this standard is only enforced when no gas is burning. After careful consideration of the circumstances in factories and workshops the Committee has recommended that a general standard be prescribed to the effect that the ventilation be such that the proportion of carbonic acid at the breathing level shall not rise during day-light or with electric light beyond 12 volumes per 10,000, and during gas-light beyond 20 volumes: the only exception to be during fogs, or in factories where carbonic acid is produced in other ways than by respiration and combustion. Compliance with this legal standard would imply that under average conditions of weather &c., the proportion of carbonic acid should be usually under 10 volumes per 10,000. It would also imply that, assuming each person to produce about 1 cubic foot of carbonic acid per hour (see above), at least 1200 cubic feet of air per person and per hour should be supplied.

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A much larger air supply is doubtless desirable, and is actually supplied in a large number of factories, but a more stringent *legal* standard would probably prove impracticable. One main cause of the bad ventilation which exists in many factories and workshops is apparently an objection to fresh air on the part of a small minority of the employees. Another not infrequent cause is insufficient warming where the work is sedentary. The laying down of the standard proposed would probably lead to the objections being overcome, and to much more attention being given to the proper utilisation of existing means of ventilation and warming. A carbonic acid standard would also supply a definite test of the degree of efficiency of any means of ventilation, and thus greatly encourage the provision of really good ventilation with a minimum of wasteful expenditure.

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