Ventilation: the human factors

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1. Introduction

Energy calculations for space heating generally neglect two important factors. The first is the contribution which the occupants and their activities make to the space heating. In the coldest weather this is 30-50% of the total heat loss.[1] The second is that people open windows and the ventilation loss is much higher than expected, particularly in mild weather. Calculations[2] suggest that this ventilation loss can constitute half of the space heating energy. The increased fabric insulation which new houses contain makes this ventilation energy loss proportionately much more important. The next research stage towards a low energy house is therefore one of controlled ventilation with heat recovery. This paper sets out to show how people operate the windows in modern British houses and then reviews the three types of ventilation need, namely physiological, dilution of contaminants and summer cooling.

2. Ventilation in practice

Dick & Thomas 1951[3] monitored twenty occupied experimental houses and showed a linear relationship between open windows and the outdoor air temperature. This accounted for 70% of the observed variance in the number of windows open and a further 10% could be attributed to wind speed with higher winds causing less windows to be open. The houses were carefully calibrated and the two most important factors affecting air change rate were number and type of window open and the wind speed. The actual window opening behaviour therefore resulted in an air change rate linearly linked with temperature in the way illustrated in fig. 1. However these houses contained different types of local heating and did not include any central heating.

Detailed field trials on modern central heating equipment were carried out at Bromley over the 1968/69 heating season. Unfortunately no window observations were made but attributing any discrepancy between the measured heat loss and the theoretical loss to ventilation resulted in a similar relationship to that of the earlier study. This is superimposed on fig. 1.

To provide a more positive correlation between window opening behaviour and the weather we arranged a daily weekday survey of 123 local houses. All were located in one area and had central heating. They had been built between ten and four years ago. Approximately half of the observations were made in the morning and half in the afternoon in a random allocation. The daily weather data was recorded at a weather station six miles north east of the houses.

The monthly averages of rooms with open windows in each house are summarised in Table 1 together with the monthly weather data. Temperature is still the dominant factor. The number of rooms with open windows is plotted as a function of temperature in fig. 2. This relationship is very similar to the earlier one of Dick & Thomas.

Let us look now at the ventilation needs of people in detail.

3. Physiological considerations

For a given activity the breathing rate is controlled primarily by the carbon dioxide concentration in the lungs, not the oxygen concentration in the room. When the inspired air contains approximately 2% by volume of carbon dioxide the depth of breathing increases. When the concentration reaches 3-5% by volume there is a conscious need for increased respiratory effort and the atmosphere becomes objectionable. The breathing rate is increased. Concentrations over 6% are dangerous.[4]

Since exhaled air contains carbon dioxide fresh air must be supplied to dilute the room concentration to an acceptable level. This maximum concentration for eight hour exposure in work areas is 0.5%[5] by volume which allows a generous safety margin for breathing comfort. The amount of carbon dioxide produced by people is a function of their activity and to a much smaller extent their diet. As the activity increases so more oxygen is consumed and more carbon dioxide released. The chemistry of metabolism leads to more carbon dioxide being created by the oxidation of carbohydrates than fats. The proportion of carbon dioxide released is slightly less than the oxygen absorbed for people on a normal mixed diet (0.85 x volume of oxygen).

Normal outdoor air contains 0.03% by volume of carbon dioxide. The fresh air needed to achieve the 0.5% carbon dioxide limit in rooms is $4.5 m^3/h$ for a sedentary person. Proportionately more is required for higher activity levels. Lower carbon dioxide levels are sometimes recommended (0.1% by volume) because it is easily measured and gives a good guide to other contaminants less readily identified.

Tolerance to oxygen concentration is very wide and can vary from 21%-13% by volume without alteration in breathing. Shortage of oxygen is therefore unlikely to be encountered in any normal building.

4. Body odours

Odours in living rooms come mostly from the occupants themselves. Healthy clean people give off odours even immediately after a bath. Such odours are not known to be harmful but do induce unpleasantness. This unpleasantness is related to the odour concentration. Sensitivity is such that it takes three times more fresh air to change an assessment from 'strong' to 'moderate' and a further factor of three to reduce it to 'definite'. Rapid adaptation to the odour occurs with exposure. Lehmberg 1935[6] found the odour generation to be proportional to the size of the person. Yaglou, Riley and Coggins 1936[7] studied the factors influencing the amount of dilution needed to render body odours acceptable. There were no sex differences in odour generation, provided that perfume was not used. Age became important for children younger than fourteen years old. Younger children created more objectionable odours and required a correspondingly larger amount of dilution air. Odour generation was only strongly related to the time elapsed since the last bath. For adults the odour generation was only slightly increased over the first six days after a bath. However the odour generation rate increased rapidly after seven days. Children generated odour in a more progressive way with elapsed time. In three days their odour acceptability was equivalent to that generated by an adult one week after having a bath (fig. 3).

An unusual feature of body odours which distinguishes them from simple chemical odours is that acceptability is influenced by both concentration and personal space. This is presumably due to the odour gradient around individuals and it is usually expressed in terms of personal volume. If several people occupy a room then the dilution air has to be increased by more than the number of people. Acceptable dilution air is therefore a function of the number of people in a room and the personal space alloted to each. This is illustrated in figure 4.

In houses and flats where cooking smells also contribute to odour, the problem is more complex. Becher and Evensen 1961[8] found in practice that the air quality was dominated by the cleanliness and habits of the individual families. This ventilation for odour control is the minimum for the fresh air supply.

5. Smoking

Fresh air is needed to dilute cigarette smoke to an acceptable level of odour and irritation. The products of combustion from a cigarette are complex and numerous, and vary with the room conditions, the smoking habits, the tobacco and its processing and packing within the cigarette. In general more tobacco is burned during the 'smoulder' period and escapes to the room than during the 'puffing' period when the smoker absorbs most of the combustion products himself. This sidestream smoke is particularly rich in carbon monoxide and contains a higher proportion of ammonia, nicotine, oxides of nitrogen and aldehydes than the mainstream smoke. Using recent chemical analyses of cigarette smoke we can estimate the order of magnitude of the fresh air dilution necessary to meet health and comfort criteria. For simplicity we shall use the unit of dilution to be the uncontaminated fresh air needed to dilute the combustion products of a cigarette.

The criteria for health vary according to the application. Safe eight hour exposure limits for industrial workers assume a healthy individual and expect a small proportion of sensitive people to experience a little discomfort. More recent recommendations deal with the home environment which may well contain sick and elderly people who are confined to that atmosphere for all the day every day. Such criteria are chosen to avoid an undesirable effect on the most sensitive person and generally are applied to the outdoor air. An analysis of the literature[16] suggests dilution on health grounds to be approximately $10m^3$/cigarette to maintain a carbon monoxide level below 9ppm by volume, and approximately twice this value for acceptability, fig. 5.

This dilution can be translated into design terms if the office population is large. Numbers of people over a hundred are expected to behave like a cross-section of a normal population. Average estimates of cigarette consumption are then valid. The most severe problem is when two people are in an office and one may be a non-smoker and the other a heavy smoker. The recommended design procedure for small offices must therefore be a flexible one such that some adjustment of individual offices is used to meet the needs of the different occupants during the life of the building.

The ventilation recommendations for rooms containing smokers are also summarised in fig. 4. Over twice the fresh air is needed for smokers compared with that necessary to dilute body odours.

6. Moisture control

Humidity affects the sensation of warmth. This is particularly important in hot climates where evaporative cooling is essential. At normal comfort temperatures the thermal effect of humidity is small. Recently McIntyre and Griffiths 1973[9] explored other effects of humidity such as dryness and pleasantness. They found that people were sensitive to non-thermal effects of humidity and preferred a 50% relative humidity condition to one at either extreme.

Moisture control can be achieved by fresh air dilution, providing the moisture content of the outdoor air is lower than the design condition indoors. For most of winter the outdoor air is approximately 90-100% saturated with water vapour (Heap 1973)[10], fig. 6. This means that the actual moisture content of air can be expressed in terms of outdoor temperature. In cold weather there will be a small amount of moisture present in the outdoor air which will increase with increasing temperature. If outdoor air is used to reduce the relative humidity in a room then this can be achieved either by a small amount of air in cold weather or a much larger amount in mild weather.

The moisture release from people through respiration and perspiration is well established physiologically. In normal circumstances a healthy 70 kg man working in a temperate climate loses approximately 400g of moisture a day from the lungs and a further 500g through the skin i.e. approximately 30g/h during sleep and 40g/h while awake. Moisture release from other sources in a house are less well defined. Smith and colleagues 1948[11] measured the moisture released from a wide variety of domestic jobs. Clothes drying was the biggest single item which could release 12 kg of water vapour from the family wash. Moisture from people was the second largest source and cooking, particularly if on a gas cooker, was third with 2 kg per day. Others have made estimates of likely daily loads with 7 kg being considered a typical daily family quantity. Comparison of various authors' estimates are shown in Table 2.

The minimum ventilation requirements for humidity control are shown in figure 7. It is very sensitive to the outdoor humidity which in turn is a function of outdoor temperature. These minimum requirements only deal with personal moisture release. In practice two or three times this amount is necessary.

The human factor of correct humidity for comfort is therefore the major motivation in determining the window opening behaviour of people in mild weather.

7. Summer cooling

The magnitude of solar radiation on the windows of a building is summarised in Table 3 (Basnett 1975).[15] Since a typical house has some twenty square metres of windows we can see that the solar gains can easily lead to overheating in well insulated houses with south facing windows. CSTB 1958[20] recommends small windows in warm parts of France and more recently Borel 1974[21] has proposed a two season ventilation system where winter ventilation deals with hygiene and a high air change summer ventilation system provides cooling.

8. Conclusions

Three ventilation seasons occur, fig. 8. The first is the coldest weather where a certain minimum ventilation rate is needed for acceptable body odour dilution. The second is the mild winter weather where the ventilation will be determined by the moisture content of the outside air. This moisture burden provides the motivation for the systematic way in which the housewife opens her windows. The third season is summer cooling. This is particularly important in well insulated houses.

Smokers pose a special problem particularly in small offices and a flexible approach to room ventilation is urged in these circumstances.

Now that fabric insulation is improving, the next step must be controlled ventilation.

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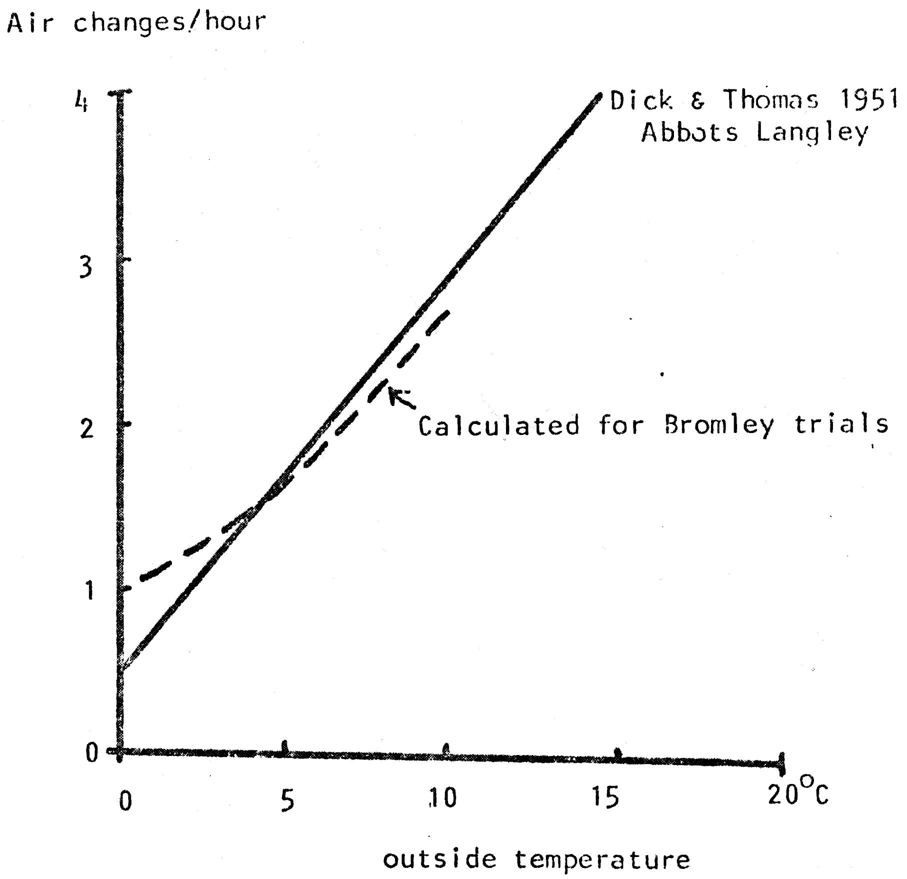

Fig. 1 Air change rate at Abbots Langley

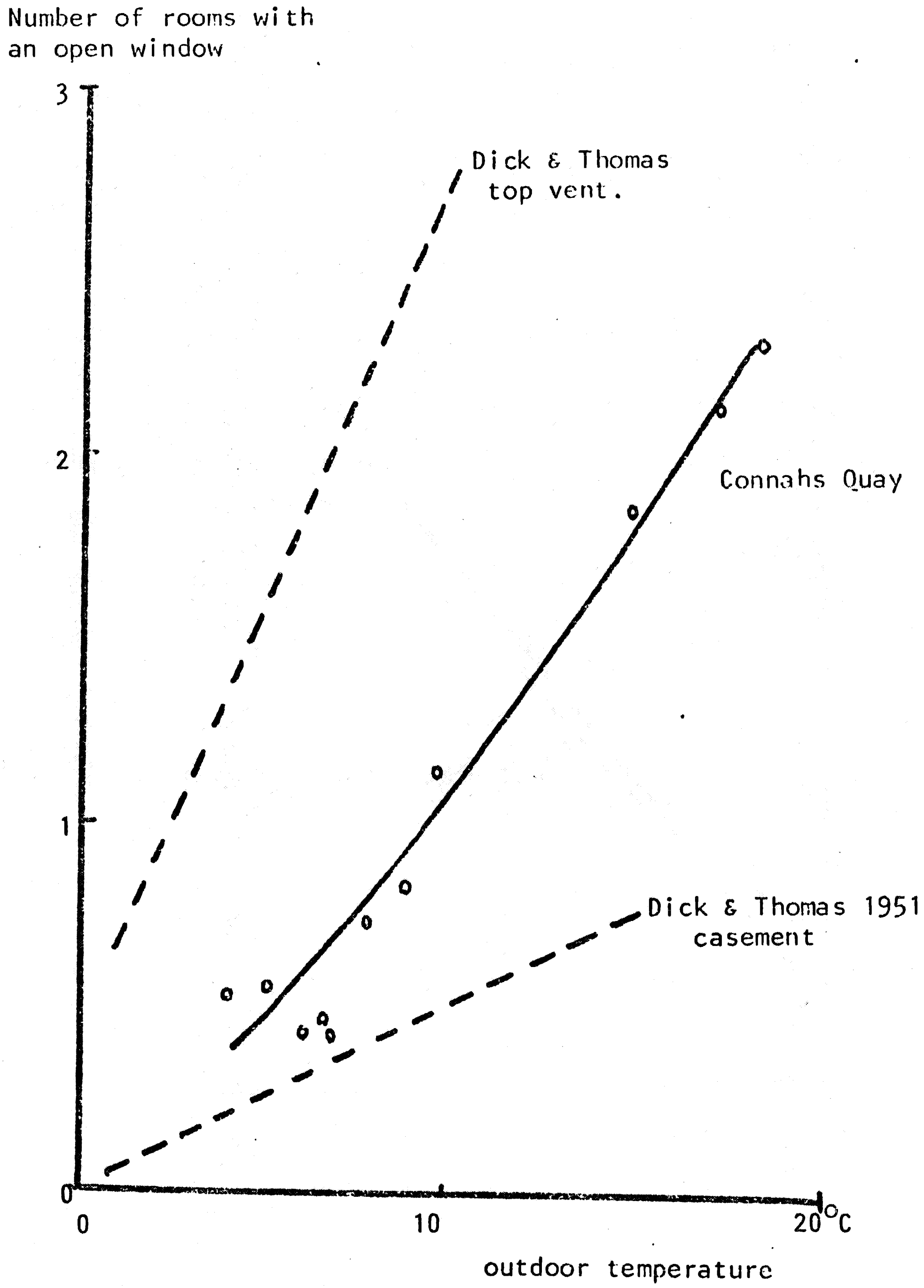

Fig. 2 Window opening behaviour at Connahs Quay 1974/1975

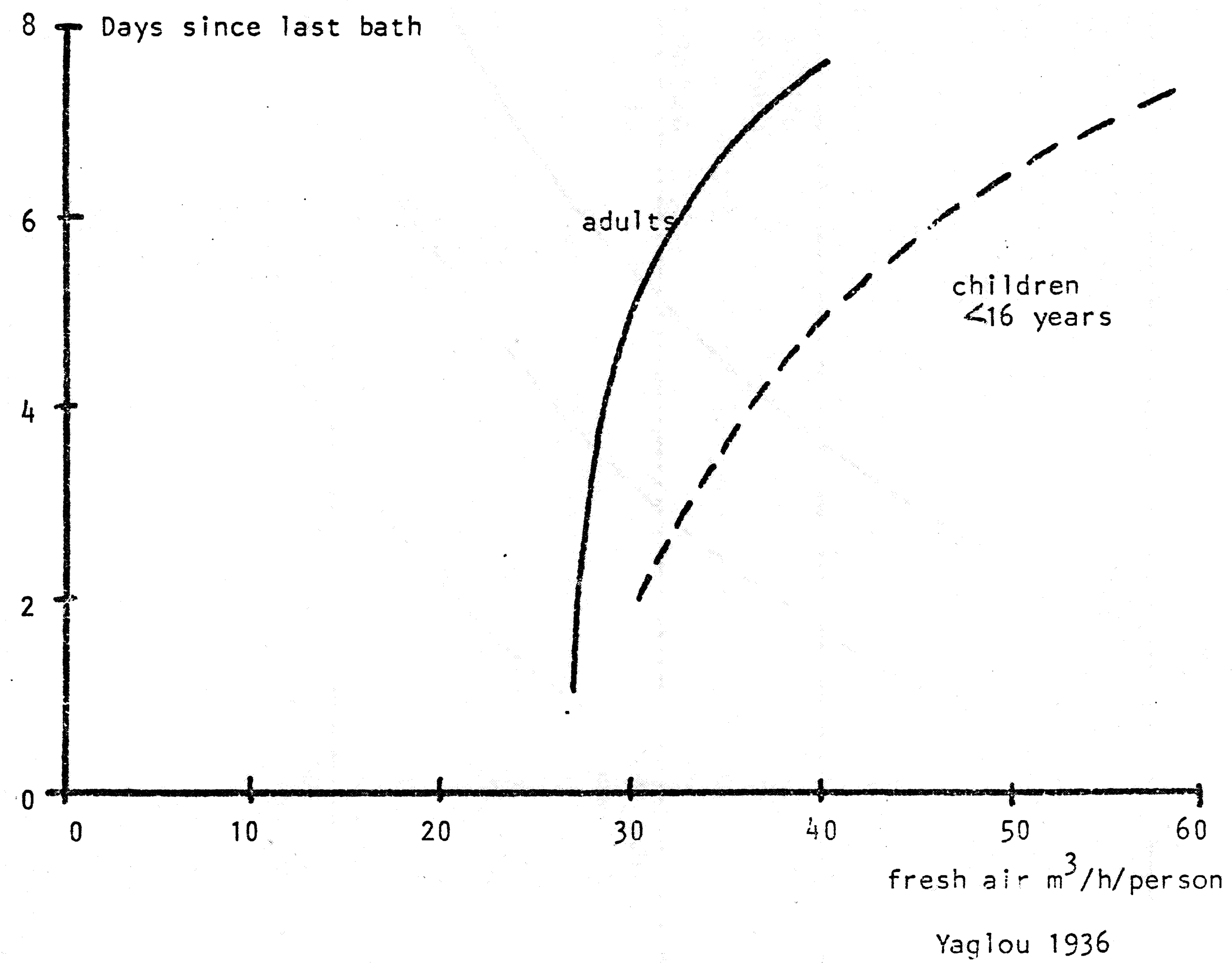

Fig. 3 Fresh air needed as a function of time since last bath

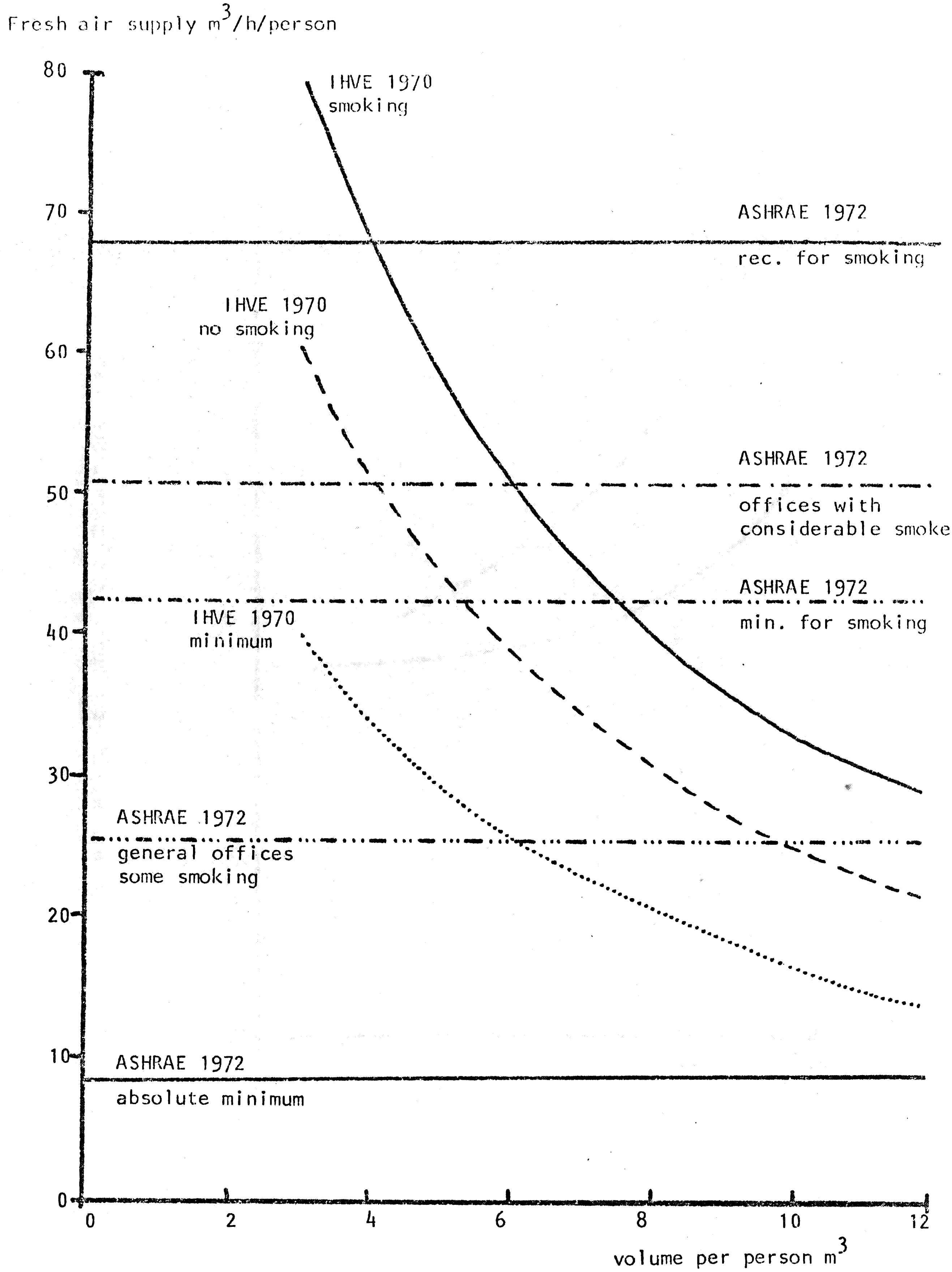

Fig. 4 Comparison between American and British recommendations

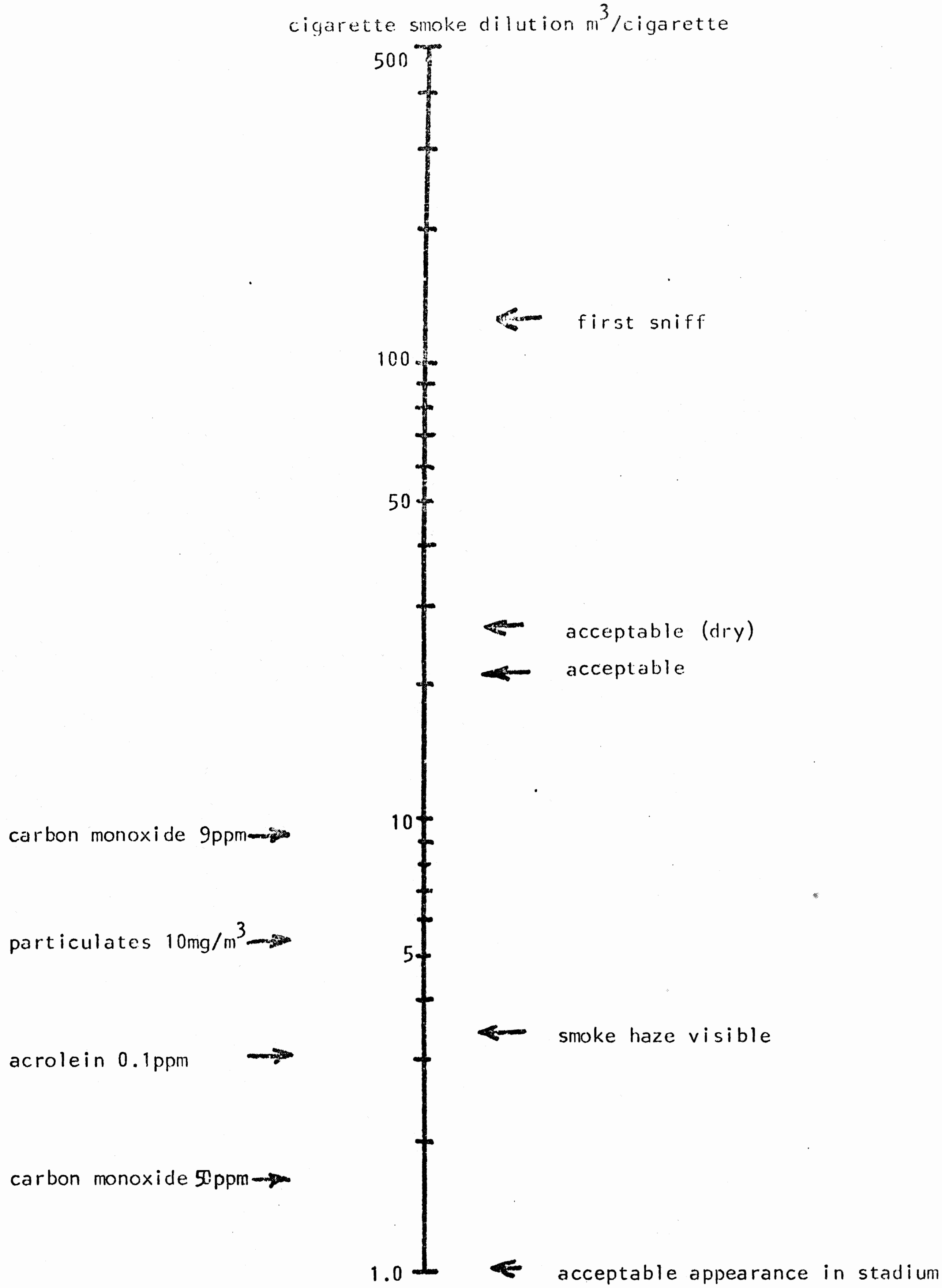

Fig. 5 Criteria for cigarette smoke dilution

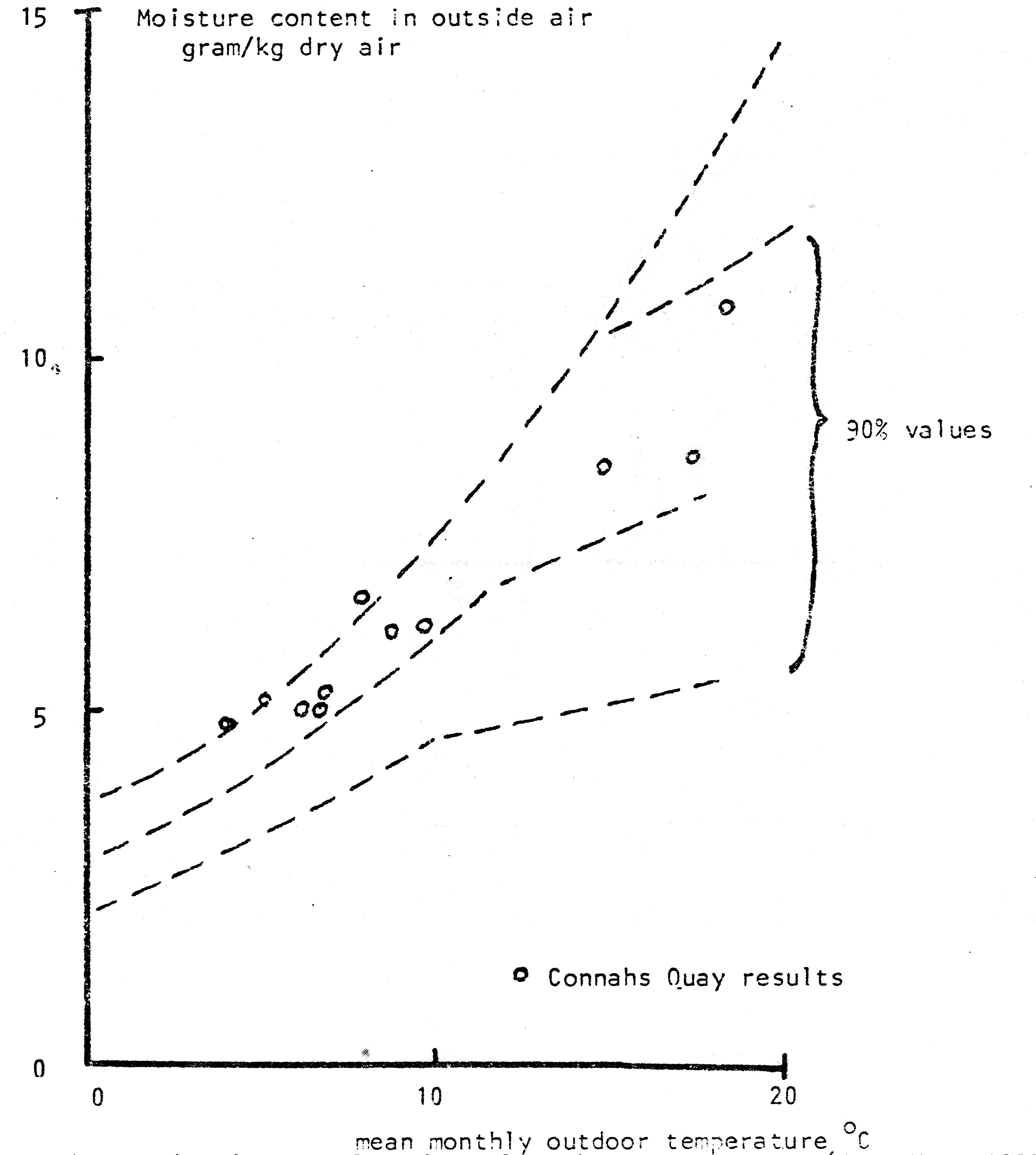

Fig. 6 Moisture in air as a function of outdoor temperature (from Heap 1973)

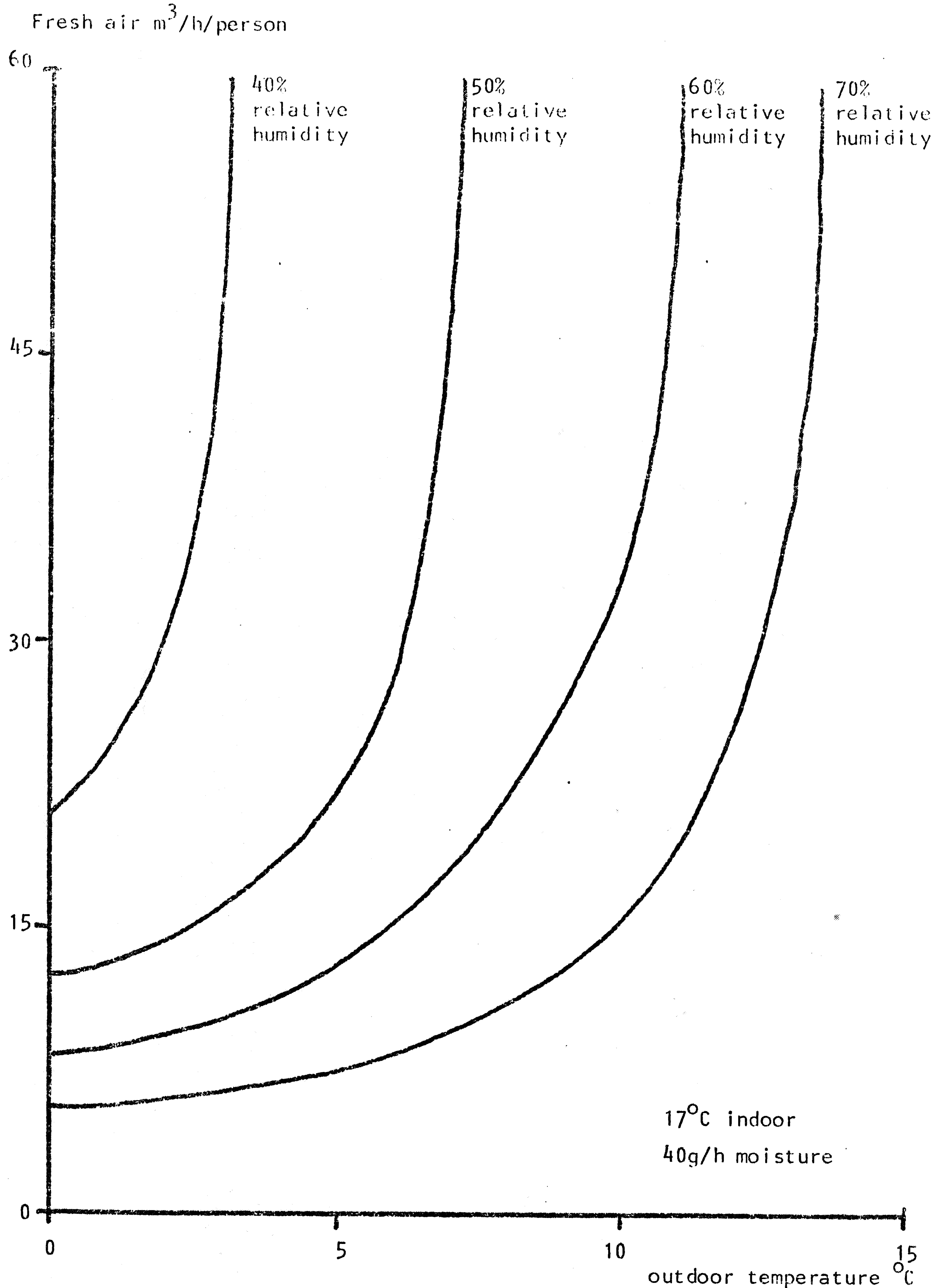

Fig. 7 Fresh air needed for humidity control

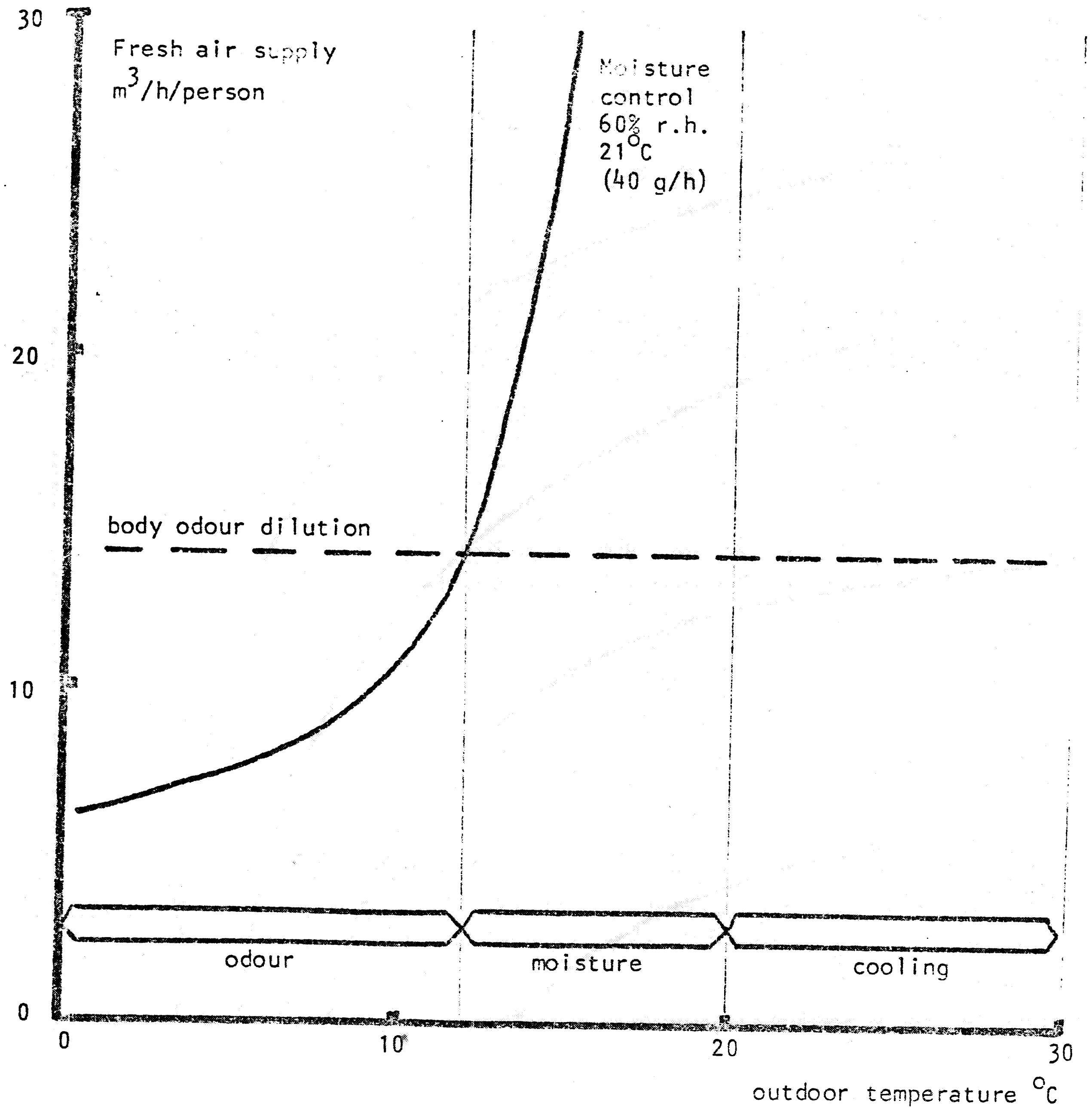

Fig. 8 Proposed ventilation seasons

Table 1 Monthly averages for weather and window opening. Connahs Quay 1974/75

Month	Rooms with windows open: Average	Mean temp. Δt °C	Average humidity g/kg dry air	Average daily temp. swing Δt °C	Average wind speed m/s	Average cloud cover (overcast = 1)	Rainfall mm
1974							
October	0.81	8.7	6.36	6.9	3.2	0.5	4
November	0.43	6.0	5.1	5.2	4.2	0.5	5
December	0.41	6.8	5.4	6.0	6.9	0.6	2
January	0.47	6.5	5.3	6.1	4.7	0.5	2
February	0.52	3.7	5.0	7.2	1.7	0.4	2
March	0.56	5.0	5.4	7.5	5.4	0.5	2
April	0.72	7.9	6.9	8.2	6.1	0.5	2
	1.16	9.6	6.4	10.0	5.1	0.4	2
June	1.87	14.8	8.7	14.6	5.5	0.3	1
July	2.13	17.2	8.8	16.8	4.6	0.4	2
August	2.28	18.5	11.0	18.7	5.3	0.3	2
September							

Table 2 Moisture generation rates in houses

Activity	AUTHOR			
	Smith 1948[11] USA	Fournol 1957[12] France	Conklin 1958[13] ≠ USA	Loudon 1971[14] England
Family size	4		4	5
Personal evaporation				
per hour		50-80 g/h	52 g/h	24 g/h
per day	5 kg		2.5 kg	1.7 kg
Floor mopping	~1 kg per kitchen	-	1.1	-
Clothes washing	2 kg		2 kg	0.5/day
Clothes drying	12 kg/week		12 kg	5 kg/day
washing			0.5 kg/day	
Cooking	15 kg/week*			3 kg/day (gas)
Breakfast	0.4 kg		0.4 kg	
Lunch	0.5 kg		0.5 kg	
Dinner	1.2 kg		1.2 kg	
Baths				
Shower	0.2 kg		0.2 kg	1.0 kg/day
Tub	0.05 kg		0.1 kg	(incl. dishes)
plants	0.02 kg			
Daily quantity	25 kg washday 11.4 kg av.	10 kg light // 26 kg medium 43 kg heavy	21.9 washday 7.9 kg ordinary	14.4 washday 7.2 average

// calculated for $216m^3$ dwelling based on release rates of 2g/h, 5g/h and 8g/h

≠ Conklin's data quoted in HMSO 1970 appears to be from Smith's study.

*42% from food, 58% from gas cooker

Table 3 Solar radiation on vertical surfaces

Maximum solar radiation falling on vertical surfaces kWh/m^2/day					
Time of year	Facing				
	N	NE NW	E W	SE SW	S
January 15th	0.26	0.26	1.15	3.5	4.8
February 15th	0.4	0.4	1.9	4.6	6.1
March 15th	0.56	0.88	3.1	5.5	6.7
April 15th	0.8	1.9	4.5	5.9	6.0
May 15th	1.4	3.2	5.3	5.6	4.6
June 15th	1.95	3.8	5.6	5.2	3.9
July 15th	1.7	3.5	5.4	5.3	4.3
August 15th	0.95	2.5	4.7	5.7	5.3
September 15th	0.67	1.25	3.8	5.7	6.6
October 15th	0.46	0.55	2.4	5.0	6.6
November 15th	0.3	0.31	1.35	3.8	5.3
December 15th	0.22	0.22	0.87	2.9	4.2

Basnett 1975