ENERGY EFFICIENT DOMESTIC VENTILATION SYSTEMS FOR ACHIEVING ACCEPTABLE INDOOR AIR QUALITY

3rd AIC Conference, September 20-23 1982, London, UK

PAPER 1 - KEYNOTE ADDRESS

THE ART OF VENTILATION

N.S. BILLINGTON, OBE, MSc, FCIBS

4 Clarewood Drive
Camberley
Surrey
GU15 3TE
United Kingdom

SYNOPSIS

The relationship between ventilation needs and methods and the growth of civilisation is traced. The Industrial Revolution is a particularly significant epoch, not least because it introduced new problems and provided new solutions. The study of physiological need began late in the development of the art.

It is questioned whether currently accepted ventilation criteria are still valid; it is suggested that ventilation is only one of several means of ameliorating the internal environment.

A requirement of any future solution is to eliminate uncontrollable variables such as wind and stack effects, and to secure the greatest collaboration between architect, builder and engineer.

1. INTRODUCTION

It so happens that when I began work, at BRS, in 1937, I was asked to study air infiltration, and in particular to correlate the air flow through window cracks with the pressure difference across them arising from wind.

I remember that the instruments were of the crudest. The manometer comprised a mica diaphragm on the cut-off base of a reagent bottle; the movement of the diaphragm was detected by a pivoted needle at its centre, and this carried a mirror so that the deflections could be photographically recorded. The response of the instrument was pretty fast; but it bore no relation to the time constant of the means of measuring air change. I have to admit that I failed completely to add one iota to our knowledge; and I was greatly relieved when I was instructed to turn to heat transfer.

On my retirement 6 years ago, I became interested in the historical development of building services, and this of course includes ventilation. The development of the art of ventilation brings to light first of all why ventilation is needed. Early civilisations, all centred around the Mediterranean and the Indus valley, were in areas where no heating was normally required. Ventilation was used rather for cooling (aided by evaporation of water from sprayed floors, fountains or damp curtains (tatties)) and to create air movement. Evaporative cooling was used as long as 3000 years ago in Assyria. Bernan[1] reports that, by means of the tattie, indoor temperatures were sometimes as much as 11°C below the outdoor shade temperature. The openings to admit light were seldom glazed, and there was clearly no question of there being insufficient fresh air supply.

> "In the Hall of Baths in the Alhambra at Granada the roof is perforated with ventilating openings, and it is not only of the best possible form for the purpose of ventilation, but the openings themselves are of

> the best possible shape, being wider at the lower extremity that at the upper; and in order that these openings may present the least possible amount of friction to the outgoing air, they are provided with short tubes of baked earth, covered with a green vitreous glazing" (Tomlinson[2])

Ingenious devices were used to increase the natural flow through the buildings - the wind towers of Yzad (Iran) - and use was made of low ground temperatures to cool air by passing it through tunnels, or over water stored in underground cisterns. The latter has been used in Iran; the former was described by Palladio, and used in Italy in the 17th century. An attempt was made to ventilate a military hospital in Cawnpore by this means in 1824; it was also used by Strutt at the Derby Infirmary some years earlier.

When civilisation spread north and west into more temperate climates, building construction changed. Windows had to be closed, both to keep out the rain and to prevent high winds causing unpleasant conditions within. The Romans probably introduced "glazing" materials - not only glass, but also hides, paper, mica and so on. We see here a change of objective - ventilation was to be restricted rather than encouraged - brought about by climatic differences. We notice, too, that there was a separation of functions, between daylighting and air supply, whereas in the earlier times, in warmer climates, the wall openings supplied both. In later periods (c 1800), after the sash and hopper windows had been invented, the window was again supposed both to light and to ventilate. This duality of function was seen by some to be wrong.

> "Heating and ventilation, especially the latter, seldom enter the mind of the builder when he projects his building; he begins as if he did not know that ventilation would be necessary; he trusts to doors and windows, to neither of which belongs the business of ventilation. The doors admit the occupants to the chambers; the windows the light; and apertures ought to be introduced to admit air for ventilation as regularly as the other openings" (Birkbeck, evidence to House of Commons Committee, 1835)[2]

In my view, it is from this duality that many of our present ventilation problems have sprung. Our best hope for the future is to follow Birkbeck's advice, to regard windows as light sources only, and to provide ventilation by other, possibly mechanical, means.

2. VENTILATION AND HEATING

Ventilation has, almost inevitably, been associated with heating[1,4]. The brazier used by the Greeks and the Romans, and the central hearth of Celtic, Saxon and British homes, all produced smoke which had to be removed. The smoke turret replaced the simple hole in the roof; the later wall fireplace and its chimney alleviated the smoke problem; but all these fires needed air both for combustion and for the removal of the smoke.

The wide flue necessary when wood (the then principal fuel) was burned in open grates also produced a large flow of air, with consequent draughts across the floor from doors and windows. Sir John Winter, in 1658, was the first to provide fresh-air ducts to supply combustion air direct to the fireplace. This attempt to separate combustion air from ventilating air was sound in principle; it was re-invented several times by fireplace designers in the following centuries; it has been "perfected" in the modern room-sealed gas appliance.

Warm-air heating (first used by the Romans in one of the versions of the hypocaust, and later in the "stein-ofen" of the monasteries of the 9th and 10th centuries) used air as the heat carrier. The initial versions made use of the warm flue gases, either directly admitted to the room (after the fire has been extinguished) or indirectly via channels in the wall. And when, in the late 16th and 17th centuries, closed stoves of various kinds were used, inventors sought either to increase the efficiency of the stove by using the flue to warm fresh air from outside for ventilation, or simply to use the stove to warm ventilating air, to avoid discomfort from cold draughts. In either case, the heating "system" provided the motive power for the ventilation. Savot, in his "Louvre" fireplace of 1624, was the first to use fresh-air ducts to supply ventilating air warmed by passage through a "jacket" behind the fireback. Gauger, in 1713, and later Leutmann (1723), developed the ideas of Savot and Winter, making use of both combustion-air and a warmed fresh air supply.

The lack of ventilation afforded by a stove was well-known, and was one reason for the discouragement of stoves in Britain. Bernan wrote in 1845:

> "It is essential for the economical effect of a stove that the room be nearly airtight .... In apartments with ill-fitting, rickety doors and windows, and a large extent of ill-glazed surface, and thin heat-absorbing walls, abounding in wind-chinks - or in general in all cases where the apartment approximates to the exposure of a field, as many English rooms do - an open fire is to be preferred."

The 1857 Commissioners, in their Report[3], said:

> "We are led to the conclusions that the outer surface of the stove should be only moderately heated, and that both the heat of the stove and the temperature of the hot air should be under regulation and easy power of control; that there should at all times be a flue or pipe for the passage of the smoke and gases; that humidity and ventilation should be specially

promoted, the two latter independently of the heating action of the stove."

They said, too, "It is absolutely necessary that water be present in the air to the amount of a degree of humidity about 66". Other references to humidity, often contradictory, occur in later literature[4], but until the ASHVE Comfort Zone was established some 50 years ago, there was little detailed information (and I suspect that was largely intuitive). Humidity as a factor in the incidence of condensation is a relatively modern phenomenon - as I recollect, there was some surprise at the occurrence of condensation when flueless gas heaters were used in the 1930's, and again at its appearance in post-war dwellings. Some at least of this can be traced to ignorance of elementary psychrometry and of the thermal and moisture properties of building materials and structures. These are just as important as humidity control in the battle against condensation.

3. THE INDUSTRIAL REVOLUTION

In the late 18th century, an important epoch began - the Industrial Revolution. It led to a drift from the land and increased urbanisation, and the replacement of cottage industry by factory work[4]. The houses built in the newly expanding towns for the factory workers were, no doubt, adequate for the period; but they were cheek-by-jowl, without proper sanitation or water supply, and they were ill-lit and ill-ventilated. (The window-tax, first imposed in Britain in 1696, and not formally repealed until 1851, was a significant factor in this). The very proximity of the dwellings, back-to-back or in terraces fronting narrow streets, reduced the cleansing effect of wind.

It was a period, too, of rapidly growing population. By the early 19th century, there was a need for more schools, and by the middle of the century, for municipal and public buildings. All these, and the factories, posed new ventilation problems, partly because of their size and density of occupation, and partly because of the demands of the processes being carried out (textiles, foundry work). There grew up a body of public "sponsors" - the newly-formed municipal authorities - which, sometimes for reasons of prestige, sought to introduce innovations in heating, ventilation and lighting into their premises; and this was, to my mind, a significant factor in the development of building services during that period. Experiment was possible.

The Industrial Revolution, however, also carried the seeds of the solution of the problems it caused - namely, motive power. Now early attempts at the ventilation of mines (c 16th century) had involved a variety of devices for moving air - bellows, windsocks and rudimentary fans operated by animals or men - and these have been described by Agricola. A man-driven fan was first used in a building by Dr Desaguliers in 1736 - at the House of Commons in fact. It was far too small, and was supplemented, and then replaced, by fires at the base of upcast shafts to induce ventilation (a return to an earlier scheme of Desaguliers in 1723). Nevertheless, the fan was here to stay and it was widely used as a part of warm-air heating and ventilating systems in the larger buildings from the middle of the 19th century onwards. Steam engines were, of course, used to drive these early fans, but were gradually superseded by electric drive by the end of the century. Some attempts were made to operate the fan from a water turbine in the early 1900's.

4. VENTILATION AND HEALTH

That there was some connection between ventilation and health was known in the middle of the 18th century. The hopper window was introduced at St Thomas' Hospital by a Mr James Whitehurst in 1784. It succeeded in reducing the mortality rate from 1-in-14 to 1-in-16. In Paris:

> "The mortality has diminished in the Hôtel Dieu in remarkable proportion .... Are we to count for nothing the destruction of all the high houses which surrounded the Hôtel Dieu? In our opinion, the pure and dry air which circulates now in every part, the sun which penetrates there, have as much contributed to its healthiness as the suppression of the amphitheatres of anatomy in its neighbourhood" (Du Châtelet, from Chadwick)

Here we see a realisation of the importance of pure air as well as adequate ventilation and heating arrangements.

Similar experiences were found in Dublin's Lying-in Hospital, where children's deaths were cut from 35% to 3% after ventilation improvements in 1784.

Dr Neil Arnott reported on the ill-health of school children. He noted that:

> "the many deplorable cases of general ill-health and mortality were attributed at first to deficiency or bad quality of food, or to any cause but the true one, want of ventilation".

In one case he examined:

> "the diet was found to be unusually good, but the ventilation very imperfect. Suitable changes were then made, and now, the same space where 700 children were by illness awakening extensive sympathy, 1100 now enjoy perfect health."

> "In the dame schools, and the schools for the labouring classes, defective ventilation is the most frequent and mischievous (cause of delicate health)."

Chadwick's Report[5] (from which the above extracts are taken) discusses ventilation and its effect on the health of workpeople, and of the ordinary family. He recommends that:

> "for the prevention of diseases occasioned by defective ventilation ...... it would be good economy to appoint a district medical officer independent of private practice."

The MOH we now have, but sadly not all are properly versed in air hygiene, and make quixotic decisions totally at variance with accepted good modern practice.

5. 19TH CENTURY DEVICES

The 19th century reformers Arnott and Galton made attempts to improve the ventilation of dwellings. Galton, in 1865, introduced his ventilating grate, in which the heat of the chimney induced a flow of air to the room via an adjacent duct. Arnott realised that ventilation required not only an inlet but also an outlet; and he devised a chimney ventilator in 1849, which was used in Buckingham Palace. It was no more than an aperture leading from near the ceiling into the chimney, and covered with a mica flap, hinged to open into the chimney. Arnott[6] also noted the possibility of heat exchange between fresh and outgoing air:

> "This double-current apparatus in an ordinary dwelling-house might consist of a number of small very thin metallic tubes, leading the hot air from near the ceiling towards the external atmosphere, and which would be included within a larger tube of which the office would be to carry pure air into the room; and currents would be produced in the two directions by suitable ventilating pumps moved like a kitchen jack by a weight wound up from time to time, or by any other power."

Tredgold (c 1820) devised a syphon ventilator, also making use of the heat of the fire.

Various window devices included a small windmill in one pane (Dr Hales ?), perforated zinc screens, louvred glass plates (Baillie, 1837) and a hit-and-miss disc (Cooper). The Tobin tube (a vertical shaft, open at the top, and communicating with the outside at the base) was popular in Victorian times (c 1878). One such had a water trough at the base of the shaft, ostensibly to trap dust from the incoming air. The Tobin tube was not a success and, shortly after its introduction, Edwards stated flatly that either the free area was too small or the incoming air immediately spilled over the top onto the floor. Worse, the provision of lids meant that all too often they were permanently closed. Yet the Tobin tube remained in use for 30 years or more, and was even recommended by an early 20th century architect.

In spite of these efforts and inventions, ventilation remained a generally neglected art. In 1850, Tomlinson wrote:

> "Not only are our dwelling-houses badly ventilated, but those buildings on which the architect has lavished all his art and skill are, for the most part, entirely destitute of special means for ventilating and are so constructed as to render the application of such means extremely difficult or even impossible."

In France, Professor Ser could say, two or three decades later:

> "One can see that the solution is no further forward, and that one has to be content with ordinary chimneys, cracks round doors and the opening of windows. (This was about hospitals - NSB). The problem has as yet no practical solution; our dwellings are unventilated."

In 1894, Professor Jacob, a pathologist, held the architect in contempt:

> "In most cases architects are content to introduce an occasional air brick or a patented device called a "ventilator" .....
>
> Real ventilation is so uncommon that the architect usually thinks this object has been attained if some of the windows can be opened. Some think that the presence of "ventilators", especially if they have long names and are secured by Her Majesty's letters patent, ensures the required end. We may as well supply our house with water by making the trap door in the roof to admit rain."

Other inventors followed - ridge ventilators and cowls (1880-1900); Boyle's patent air pump; the simple air brick to meet the demands of building by-laws; the Knapen system, with porous tubes at intervals in the base of external walls, and at high level in the internal ones (1925).

The advent of the electric fan inspired inter alia Thomas (1906)[7] to suggest their use to ventilate wc's, and that they should also be operated by the seat.

6. HUMAN NEEDS

Knowledge of human physiology was almost non-existent until the late 18th century. The first quantitative studies of metabolism were those of Crawford in 1777, who measured the heat production of a guinea pig. The experiments were repeated by Lavoisier and Laplace in 1780; they also studied the respiratory exchanges, and showed them to be related to heat production. Lavoisier noticed that the consumption of oxygen was one-twelfth less at

26°C than at 12°C. Respiration in humans was studied by Seguin (1789), Dulong (1822), Regnault, Davy, Péclet and Dumas in the first half of the century. Dumas found that a person exhaled 330 l/h, the breath containing 4% CO_2, and that he metabolised 10 g/h of carbon and hydrogen, liberating 93W. Péclet[8] went on to deduce that the water loss by respiration and evaporation was 61 g/h (- 44W), and hence, by difference, the sensible heat loss was 49W. Péclet, Roscoe and Pettenkofer went immediately from a knowledge of respiration to make estimates of the fresh air needed to remove water vapour and/or odours: none made any statement as to physiological need.

(Some rather strange ideas were current at the time. Thus Burns[15] wrote in 1850:

> "It is not only through the lungs that pure air exerts a beneficial influence upon the body; the skin, pierced by its numerous pores, also exercises a function of considerable importance ..... In a healthy person, the inhalation of pure, and the exhalation of impure air, through the medium of the skin, goes on with considerable regularity. It has been ascertained that pure air, by being in contact with the skin, becomes chiefly carbonic acid gas.")

Arnott and Péclet both knew that the minimum needed to support life was a mere 330 l/h. Box assumed 620 l/h, but to determine the total fresh air requirement, he added the quantity needed to remove water vapour and combustion products (arriving at 7 m^3/h rising to 14 m^3/h in crowded rooms)[9].

Pettenkofer established a School of Hygiene at Munich c 1865. He measured the exhalation of CO_2 at varying rates of activity.

Lavoisier attributed to CO_2 "the malaise often experienced in crowded halls, the malaise generally attributed to warmth alone". Leblanc believed (1842) the culprit was depletion of the oxygen content instead. But for over 100 years after Lavoisier, CO_2 was usually held to be the cause of discomfort, although Pettenkofer (1862) thought the unpleasantness was due to organic materials exhaled or shed from the skin. (However, he was prepared to accept CO_2 as an index of vitiation, and proposed a maximum CO_2 of 0.1%, based on odour).

It was Haldane and Hill who, in 1913, showed conclusively that no physiological distress occurred even at CO_2 levels of 3 or 4%. Any discomfort was due to excessive warmth (originally proposed by Hermans in 1883 - but cf. Lavoisier).

Subjective experiments were carried out by D.B. Reid[10]: he concluded that 10 ft^3/min fresh air were needed. He says:

> "This estimate is given with much diffidence and only as an approximation. It is the result, however, of an extreme variety of experiments made on hundreds of different constitutions supplied one-by-one with

given amounts of air ..... Those who became the subject of experiment were for a time included in an air-tight box, and provided with a long glass pipe to draw the air they inspired from any part of the box in which they were placed. A small seat is represented on one side and on the other a series of trays on which materials could be placed either for the purpose of absorbing various ingredients from the air on special occasions, or of communicating different materials to it. On other occasions a more complicated piece of apparatus was employed, consisting of a large iron frame, glazed like a window, and connected with a pump, by which air of any quality could be supplied. The air entering is dried or charged with any peculiar materials."

He recounts an amusing story of the effect of ventilation upon diet:

"Some years ago, about 50 members of one of the Royal Society clubs in Edinburgh dined in an apartment I had constructed, where, though illuminated by gas, the products of its combustion were essentially excluded, as they were all removed by a ventilating tube connected with, but concealed in, the drop of the gothic pendant in which the lights were placed. Large quantities of mild atmosphere were constantly supplied, and passed in quick succession through the partment throughout the whole evening, the effect being varied from time to time by infusing odoriferous materials, so that the air should imitate successively that of a lavender field, of an orange grove, etc. Nothing very special was noticed during the time of dinner by the members, but Mr Barry of the British Hotel, who provided the dinner and who, from the members of the club being frequently in the habit of dining at his rooms, was familiar with their constitutions, showed the committee that three times the amount of wines had been taken than was usually consumed by the party in a room lighted by gas, but not ventilated."

Roscoe, working for the 1857 Commissioners, showed that 17 m^3/h was not enough to clear odours in Wellington Barracks, and that 25 or 35 m^3/h ought to be provided. De Chaumont's later work (1875) showed that odours were not generally perceived if the animal CO_2 was less than 0.04%, equivalent to a fresh air supply of 42 m^3/h. These figures were much higher than Péclet proposed, on an odour basis, for prisons and schools, namely 6-10 m^3/h per occupant.

Throughout the 19th century, there were, then, several hypotheses as to the cause of air vitiation. But perhaps because it was easy to measure, CO_2 was almost universally accepted as a criterion of ventilation. "Animal" CO_2 was limited to 0.1% or less, corresponding to a minimum air supply of 28 m^3/ (1000 ft^3/h).

Yaglou's work of 1936 has, of course, been the basis of modern practice. It purports to yield odour-free atmospheres. Its distinct features are (a) reference to social class and (b) relation to volume per person. (Picard in 1897, and Box and others before, had noted the latter).

Although Billings, in 1884, had proposed extra fresh air where smoking was allowed, and Yaglou had worked on this, the best review is probably that of Brundrett[11] a year or two ago. He concluded that carbon monoxide concentration is as significant as the smell, and that an acceptable atmosphere might require as much as 40 m^3 per cigarette.

It is clear that from an early stage, odour was regarded as the main contaminant, and that sufficient air to make it imperceptible would be enough to remove the other contaminants (water vapour, heat) and to support life. In passing, we should note the Synthetic Air Chart devised by Dr E.V. Hill in USA (1921), and this included bacterial concentration. Wells and Wells (1936) and others later have laid particular emphasis on air hygiene, and much work has been done on bacterial sprays, irradiation and ozone. The use of ozone as a deodorant was suggested in 1909 by Lubbert, and it was used by Rietschel in 1911, though he said it could never replace ventilation. It has been reported that ozone at a concentration of 0.015ppm is sufficient to mask body odours, and reduce fresh air requirements by 50%. The use of activated charcoal as an odour absorbent was advocated in the middle of the 19th century by Professor Stenhouse of Bart's, while in the early 1900's, the Pullman Car Company experimented with its use.

One must mention, too, the ion content of the air as a possible factor in well-being. The malaise associated with the föhn, the sirocco and similar winds is well-known; there is believed to be a high positive-ion content when they are blowing. Atmospheric electricity was studied by Coulomb in 1875, and air ionisation by Elster and Geitel in 1900. It seems to have been assumed in the early years of this century that air was ionized by radio-activity in dust (and would therefore be de-ionized by filtration and washing). Napier Shaw was unable "to state anything definite as to the effect the treatment of the air in the modern systems of ventilation exercises upon its electrical activities" (c 1905). Modern research is somewhat inconclusive as regards the benefits of high negative-ion content; but it appears to be fairly well established that air which has traversed a system of ducts has suffered a loss of negative ions.

These several factors raise a number of important questions:

(i) How far is Yagou's work relevant to present-day standards of personal hygiene?

(ii) Can fresh-air requirements be reduced by the use of odour absorbents, bactericidal means, ion generators, dehumidifiers or coolers? - in other words, reduce the general or special contaminants by means other than dilution of fresh air.

A reduction in fresh-air supply would yield vast savings of energy: the proportion of energy needs simply to heat the ventilation air is rising as the thermal insulation of buildings is improved.

From what I have said, you will I hope draw the conclusion that ventilation is only one of several techniques which we can call on to ameliorate our atmospheric environment, or correct deficiencies and dangerous or unhealthy conditions. Dickson, in his paper to this Conference, notes that the internal environment must be so good that the occupants do not need to open the windows - if indeed the outdoor air is itself sufficiently pure and clean and the external noise tolerable. We should, I think, use one or more of these techniques, as may be appropriate, in conjunction with ventilation (whose function is, essentially, to provide the oxygen we need to live). We do not have to assume that ventilation is either the only or even the cheapest means of removing contaminants.

7. AIR DISTRIBUTION

I have said that Arnott and others had realised that inlets and outlets are both needed to ensure a flow of air (and also a satisfactory degree of air movement). The mere provision of these openings does not of itself however ensure that all parts of the space are efficiently ventilated; their size, disposition and siting are crucial in this. There has, I suspect, been too little research on this aspect of the problem. The argument concerning "downward" or "upward" ventilation has raged, without real conclusion, for over 100 years. It was Box, I think, who recognised that with natural ventilation, the summer problem was different from the winter one, and that the "natural" direction of air flow might be reversed from one season to the other. He saw, too, that the problem was different yet again when warm-air heating and/or plenum ventilation was employed. The problem is three-fold:

(a) how to avoid short-circuiting and consequent stagnant areas.

(b) how to avoid draughts, and in particular cold air in winter.

(c) how to secure optimum removal of contaminants from the breathing zone.

Even today, with air conditioning, i.e. winter heating and summer cooling, I doubt whether any one position for the entering air openings is appropriate all the year round. There is, in short, no single answer, applicable to all seasons and to all modes of heating and ventilation, to the question of siting inlets and outlets.

One might perhaps say that the problem of introducing air (either naturally or mechanically) can usually be solved in a technical or engineering sense. It may however often be defeated by architectural or aesthetic considerations - perimeter openings at floor level may not be possible for structural reasons, or they may be unacceptable since they may become depositories for dust or other debris, or the openings may unduly restrict the placing of furniture.

8. MOTIVE POWER

Ventilation requires a motive force - ça va sans dire. Three sources are available:-

- heat, either the stack effect (indoor-outdoor temperature difference, or induced by fires, gas jets, hot water pipes, etc.)
- wind pressure
- mechanical means (bellow, fans, pumps, etc.)

The natural forces are variable and ventilation uncertain. One can never ensure ventilation in still-air conditions in the spring and autumn of temperate climates, for neither wind nor stack effect then exists. This is the central problem. When the natural forces are in play, something can be done to restrict the maximum air flow. This is usually left to the occupant (who is, by and large, an inefficient control) by window opening or hit-and-miss ventilators, though attempts have been made to design automatic variable-resistance devices with the object of fixing a maximum flow.

It was this uncertainty which led inventors to turn to means of assisting the flow of air. Fires at the base of special chimneys, the heat of gas jets, the fires of a ship's galley, steam and water jets have all been used from time to time. The circulating pipes of hot water heating systems have been used in dwellings, prisons and hospitals to induce air movement in upcast shafts. All these were intended to extract air; the fresh-air was to find its own way into the building. It is not clear from their summary whether Sherman and Grimsrud have something of this sort in mind.

Fire extract had some merit. It was used in a soap works to destroy the odours (the boiling vats were enclosed by a hood, and the vapours led to the ashpit of the fire); and in a hospital at St Petersburg to sterilize the air to be discharged.

An ingenious device was described by a Dr Anderson[9] in 1800. It was intended to ventilate, both winter and summer, by the heat of the sun. Its essential component was a chimney connected to an aperture in the ceiling of the room to be ventilated. This chimney had its south side made of glass, and the sun shining upon it warmed the whole length of the chimney, causing the air within to ascend. Anderson further supposed that if the room were constructed with double walls, the cavity being also connected to the chimney, then in summer the inner rooms could be kept cool, for the sun's heat would be carried away by the air current in the cavity. And if the whole outer south facade of the room were of glass, the heated air in the cavity would be used to warm the room in winter. This, we see, was effectively a Trombe wall, such as is being currently investigated as a means of using solar energy.

9. ARCHITECT AND ENGINEER

Much of the success or failure of many if not all of these schemes (and indeed of later mechanical systems) rests upon the relationship between architect, builder and inventor/engineer. When the architect and ventilation designer were at odds (as were Barry and Reid over the House of Commons in 1834), the scheme failed; when they were able to work together, as Reid was able to do with Lonsdale, the architect of St George's Hall, Liverpool, in 1851, it was an outstanding success. And with extract systems, poorly fitting doors and windows give rise to draughts, however efficient the extraction may be.

We have here a clue to future success. The building must be designed with ventilation in mind; the services cannot just be tacked on as an afterthought to a pre-existing concept. To put it the other way round, we have to decide at the outset what sort of ventilation is necessary - mechanical or natural, plenum or extract - and indicate to the architect and builder the quality of construction needed. A recent Norwegian paper by Trond Ramstad has highlighted the necessity for attention to building details.

10. CALCULATION OF AIR FLOW

I believe that the first attempts to compute infiltration rates were made by Tredgold[12] in about 1820. Certainly he calculated the air flow through the cracks round doors and windows (arriving at 11 ft^3/min for each unit), and went on to discuss the ventilation of greenhouses to prevent overheating in summer. His work was founded on the stack effect. It was largely ignored, and recourse was had to empirical statements (of Hoffman and Raber, 1913, who thought that natural infiltration was impossible to determine, and recommended 2 ac/h be assumed).

About the turn of the century, the study of meteorology began to be combined with that of ventilation. J.W. Thomas seems to have made some experimental determination of wind pressure on buildings in about 1900 - 1901, and he appreciated its effect on natural ventilation. Napier Shaw in 1908 developed the electrical analogy for computing air flow in networks, building on Murgues' concept of an equivalent orifice. This work, too, was neglected for half a century, until revived by Hinsley (who in about 1950 built an analogue computer for solving mine networks), by Harrison in 1961 for buildings, and by others since, with further computer models.

But when all is said and done, the prediction of infiltration or air flow depends on the quality of the input data - in particular, wind pressures, goodness of fit of components and structure, and permeability of the fabric. All these are variable. We can give calculations based on historical data; we cannot predict what will happen, at the drawing-board stage.

If this is a negative attitude, it brings me back to saying that the variability must be eliminated as far as possible in the design and that we should use the more nearly calculable mechanical ventilation.

11. HALTING PROGRESS

It is I think worth noticing how technical progress can be halted or reversed by misguided or erroneous opinions, firmly held.

Mechanical ventilation of schools was relatively common in Britain in the early years of the century. True, its design was a trifle odd to our eyes, e.g. ductwork:

> "When the ducts are of such size that it is possible to walk through them, it is reasonable to expect school masters and managers to personally supervise them and their cleanliness, whereas with small ducts they are left to the tender mercies of the caretaker, with too often a fatal result as to this necessary condition."[13]

But the LCC came to the conclusion that mechanical ventilation and heating in schools was a failure, "because teachers manipulated the apparatus in such a way that the heating could not be relied on and was made useless". This seems to have been the death knell of mechanical ventilation in British schools. Later, in 1928, H.M. Vernon[14] was totally convinced of the virtues of natural cross-ventilation, and preached that mechanical ventilation should be avoided. He went so far as to advocate open-air schools, since because they were good for tuburcular patients, they would be equally good for healthy children. His colleague, Bedford, though, observed that the poor little devils were never warm. Not until after World War II was mechanical heating and ventilation again seen in British schools.

An older story of official obstruction relates to the efforts of Desaguliers and Sutton to improve the ventilation of warships[9]. At the beginning of the 18th century, troops embarked for an expedition against the Spaniards were taken ill and had to be relanded. In consequence, the Lords of the Admiralty asked Dr Desaguliers to demonstrate his newly developed fan. Although the trial seems to have been successful, the Surveyor to the Navy, Sir Jacob Ackworth, would have none of it. This was about 1736. Shortly afterwards, Samuel Sutton devised a method of ventilation, consisting essentially of leading pipes from the space to be ventilated to the ash-pit of the galley fire, the draught of the fire causing air to be drawn from the spaces through the pipes. Sir Jacob said that no trial should be made if he could help it. Eventually, in 1741, the Admiralty was induced to order a trial. Sir Jacob welcomed the distinguished company (Lords of the Admiralty, Navy Commissioners and some Fellows of the Royal Society) by saying, "I am sorry that you are come to see the trial of such a foolish experiment, that I tried myself yesterday, and it would not shake a candle". In fact the trial was successful. After much delay, the Admiralty stated that:

> "the apparatus does not come up to expectation, and the use thereof is dangerous and liable to accidents by fire".

But they gave Sutton an ex gratia payment of £100.

12. RESEARCH

I confess to wondering whether some current research is not being directed at the wrong questions. Studies of natural infiltration through door and window cracks, due to wind or stack effects, are, almost by definition, statistical studies: the results cannot, I suspect, be used in design because of the innate variability of building components and of wind force. We can eliminate much of this variability if we build tight structures, i.e. no opening windows, and provide ventilation by mechanical (controlled) means - or at least by designed openings such as "constant-flow" ventilators. These approaches are seen, in their separate and opposing ways, by Dickson and by Johnson and Pitts.

Computer models are valuable only for studying the effect of varying the parameters; they rely on historical data; they cannot of themselves provide a solution which can go straight to the drawing-board. And research aimed at a detailed understanding (even perhaps the minutiae) may well be irrelevant to the central problem, which is to ensure a satisfactory and healthy environment at minimum cost.

Also, why the emphasis on dwellings? True, this Conference relates specifically to them; but are there no problems in factories, schools, offices? - or have we already made up our minds that in these cases, all the decontamination methods, and mechanical ventilation, are appropriate and indeed necessary and worthwhile? Nobody has suggested that although central heating and fluorescent lighting is appropriate for non-domestic conditions, these are unsuitable or uneconomic in dwellings. In the same way, I do not think we can maintain that mechanical ventilation is necessarily out of place in the home.

13. CONCLUSION

The burden of my talk is to urge a broad approach to the problem of ventilation, not only in dwellings, but in all buildings. An occasional backward glance may bring to light a useful idea, impracticable at the time of its conception, but which has been made possible by technological advance. We do well to understand, and perhaps to query, some of the axioms of the present day, for it is likely that circumstances have changed since they were first formulated. Perhaps, above all, we should avoid the blinkered approach, the concentration on one or other aspect, without questioning its relevance to the central problem. One can often overlook the wood while one is examining the trees. Quite often the problem put to the research worker is not the crucial one, but only the Director's perception of it. The real solution may perhaps be found by going round an obstacle rather than tackling it head on. Let us not forget why we need ventilation and why we need to control it. There are many ways of killing cats. And always remember that any successful solution must involve the heating designer, perhaps the lighting and acoustic engineers, and certainly the architect, the builder and the occupant.

REFERENCES

1. BERNAN, W.
"History and art of warming and ventilation"
Bell, London, 1845

2. TOMLINSON, C.
"Rudimentary treatise on warming and ventilation"
Weale, London, 1850

3. "General Board of Health: Report of Commissioners appointed to enquire into the warmth and ventilation of dwellings"
HMSO, London, 1857

4. BILLINGTON, N.S. and ROBERTS, B.M.
"Building services engineering - a review of its development"
Pergamon, Oxford, 1982

5. CHADWICK, E.
"Report of the sanitary condition of the labouring population of Great Britain 1842"
(Ed. Flint) (Edinburgh UP, 1965)

6. ARNOTT, N.
"On warming and ventilation"
Longman, London, 1838

7. THOMAS, J.W.
"Ventilation, heating and lighting of dwellings"
Longman, London, 1906

8. PÉCLET, E.
"Traité de la chaleur"
Massone, Paris, 1861

9. BOX, T.
"Practical treatise on heat"
Spon, London, 1868

10. REID, D.B.
"Illustrations of ventilation"
Longman, London, 1844

11. BRUNDRETT, G.
"Ventilation requirements for smokers"
ECRC Report M870, Electricity Council, 1975

12. TREDGOLD, T.
"Principles of warming and ventilation"
Arch. Lib., London, 1824

13. YATES, W.
"Mechanical ventilation"
Proc. IHVE 3 (1902) p6

14. VERNON, H.M.
"Methods of heating and ventilation in schools"
Proc. IHVE 27 (1928) p146

15. BURNS, R.S.
"Practical ventilation"
Blackwood, London, 1850