PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Air Pollution in Towns in the United Kingdom

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IV. DISPERSAL OF AIRBORNE EFFLUENTS

Air pollution in towns in the United Kingdom

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The daily observations of smoke and sulphur dioxide that have been taken over the past ten years at some 1200 sites throughout the United Kingdom for the National Survey of Air Pollution, have provided a great deal of information on pollution in towns. An examination of this material is made to assess changes that have been occurring in levels of pollution in relation to the changing pattern of fuel consumption, and is used in trying to forecast the position in the next 15 or 20 years. A comparison is also made between pollution in towns in different parts of the U.K. The question of what levels of pollution may be tolerated is also considered.

The part that aerodynamicists, architects and town planners can play in reducing urban pollution is discussed and an attempt is made to see what guidance can be given to them so that as far as pollution is concerned, the new and renewed towns of the future may avoid the mistakes of the past and therefore not need the costly remedial measures that now have to be taken in towns built in the past.

The application of the principles of architectural aerodynamics to town planning can provide one of the more elegant and economically acceptable solutions to the remaining problems of air pollution in towns in the United Kingdom. As an introduction to a discussion of these possibilities, this paper sets out the present state of air pollution in this country in relation to the progress that has been made in the last decade and the changes that are likely to take place in the next.

The United Kingdom is particularly well placed for such a study because not only can emissions of pollutants be calculated from the detailed statistics on the use of fuels for various purposes that have been published annually by the Ministry of Power, but observations of smoke and sulphur dioxide concentrations in the air are now available for some 1200 sites, covering the whole country systematically as part of the National Survey of Air Pollution. Observations under the Survey have been made since 1961–2 but at many sites records go back very much further.

Data for emissions of smoke and sulphur dioxide for the United Kingdom as a whole are given in the upper part of table 1. The lower part of the table is based on the White Paper 'Fuel Policy' presented to Parliament by the Minister of Power in 1967.

Smoke—the United Kingdom as a whole

The remarkable fall in emissions of smoke by 60 % over the period 1951 to 1968 has been achieved in spite of a 10 % increase in population and a 17 % increase in the annual gross energy consumption. The changes may be examined in more detail in figure 1, where the industrial and domestic emissions are separated.

Practically all the smoke emitted by industry arose from the incomplete combustion of coal in inefficient boiler plant and furnaces. The emission of dark smoke by industry was prohibited by the Clean Air Act of 1956, except under special circumstances, and a period of grace was allowed to give time for boilers and furnaces to be adapted to comply with the Act. This could be done by adapting them to burn coal efficiently or by abandoning coal altogether in favour of oil. The arrangements under the Act were such that these changes had to be virtually completed by 1961. The effect of the industrial provisions of the Act is clearly reflected in the sharp drop starting in 1955, when the Act was under discussion, and ending in about 1962. It is worth

Table 1. Emissions of smoke and sulphur dioxide in the U.K.

	smoke	sulphur dioxide
	million tonnes	
1951	2.36	5.12
1952	2.33	5.10
1953	2.31	5.15
1954	2.33	5.35
1955	2.33	5.49
1956	2.22	5.43
1957	2.09	5.49
1958	1.97	5.61
1959	1.83	5.64
1960	1.73	6.00
1961	1.62	5.96
1962	1.50	6.26
1963	1.39	6.34
1964	1.28	6.13
1965	1.20	6.19
1966	1.11	6.07
1967	1.01	5.87
1968	0.93	6.01
1975	0.60	5.46

noting that industry complied with the requirements of the Act to a considerable extent by replacing coal with oil, as the industrial coal consumption fell by 33 % over that period. It has since fallen by 50 % from its level in 1962. This continued replacement of coal by oil suggests that it is reasonable to credit the Act with having greatly accelerated developments which would, however, of themselves, have taken place slowly but inevitably. In fact, like other successful legislation the Clean Air Act is 'swimming with the tide' of industrial development.

The domestic provisions of the Act gave Local Authorities power to set up 'smoke control areas' in which the burning of fuels other than 'smokeless fuels' is prohibited, and they were encouraged in particular to use these powers in those parts of the country specially subject to high pollution—the so-called 'Black Areas'. Many local authorities applied these powers vigorously but others made, and are making, more modest progress. The net result has been that emissions of smoke from domestic heating started to fall in 1955, when the Act was under discussion, and have continued to do so ever since as more and more smoke control areas are set up. This is shown in figure 1. When the Act was planned it was considered that coal would be replaced almost entirely by coke or, to some extent, by other premium solid smokeless fuels (anthracite, semi-cokes, etc.) as these would come nearest to coal in price and its replacement by them would cause the least change in the heating habits of the householders concerned, who were, however, left free to choose oil, gas or electricity if they preferred them and could afford the extra cost. Up to about 1963 this expectation had been fulfilled but since then the consumption of coal plus solid smokeless fuels has declined as oil, gas and electricity have made increasing

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inroads into the domestic market. The reasons for this are not far to seek as the changing social pattern, with more women working outside their homes, and greater stress on labour-saving and cleanliness, has resulted in the decline of the traditional British coal-burning open fire as gas, oil, or electricity produce the heat that is now only required for an hour or so in the morning and a few hours in the evening much more conveniently and competitively. Among the better off more money is spent on comfort, in the form of central heating, and this replaces the dirt and draughts of the open fires.

These changes in heating requirements are particularly opportune with the obsolescence of the classical gas industry and the consequent disappearance of gas coke from the market during the next decade or so. The authors consider that the difficulties this will put in the way of the

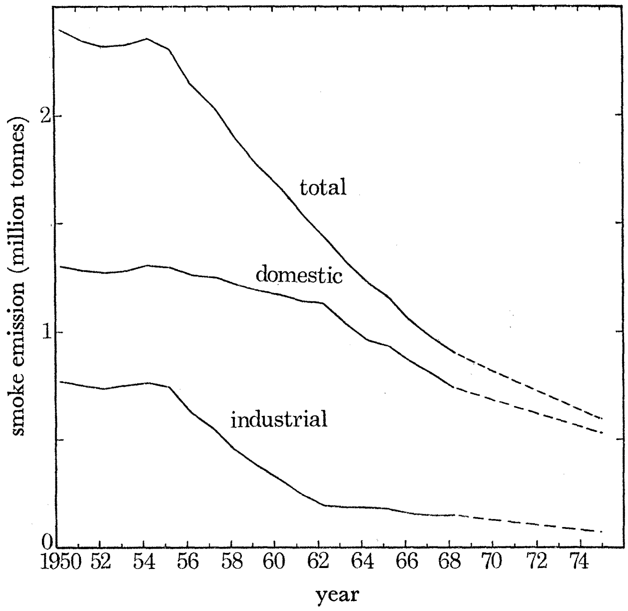

FIGURE 1. Smoke emissions in the United Kingdom. ——, Estimated from actual fuel consumption; ----, estimated from forecast fuel consumption.

vigorous application of the domestic provisions of the Act will be more than offset by the effects of the social changes mentioned in the preceding paragraph, and that the target set for 1975 by the White Paper—see table 1 above—will be reached comfortably.

Whatever the details of the ventilation of towns may be, the rate of emission of pollutants will be the basic factor in determining the concentration near ground level and to which the inhabitants are exposed. Other factors are the meteorological conditions, which change erratically from year to year and result in annual concentrations falling unpredictably above or below the mean trend line, and changes in the structure of towns brought about by re-housing and re-development which in general lead to a decrease in housing density and hence a decrease in concentration of pollutants although the emission may have remained constant. A comparison must therefore be made between the observed trend of smoke concentrations, as given by the National Survey, and the emission trends shown in figure 1.

For each pair of consecutive years all the sites for which valid annual averages were available—normally of the order of 500—were picked out and divided into the twelve regions used by the Registrar General for statistical purposes. The smoke concentration was averaged for each region and an average for the United Kingdom obtained by weighting each region according to population. The trend diagram given in figure 2 was then obtained by putting together the sets of two consecutive years. It shows clearly the erratic effects of weather, and it shows an overall downward trend corresponding very closely to the downward trend in total emissions of smoke. The emissions are shown in figure 2 by the dashed line, the scale being adjusted to show the closeness of the fit to the best advantage.

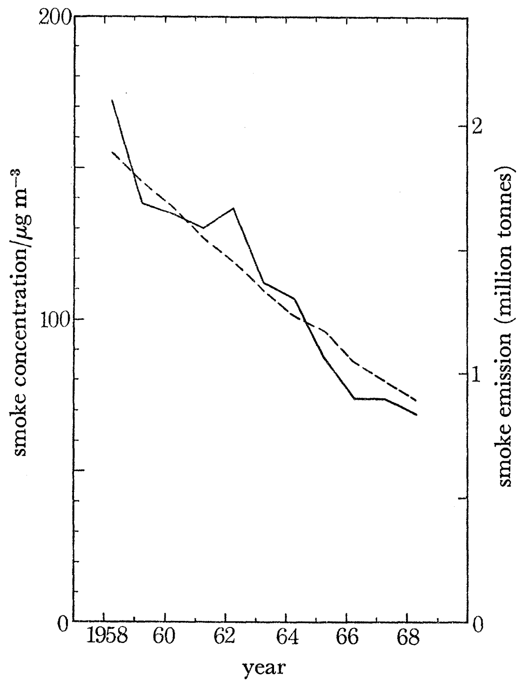

FIGURE 2. Smoke concentrations and emissions in the United Kingdom. ——, Average concentration; ----, emission.

It may be concluded that the curve showing the change of total emission since 1950, as given in figure 1, is a sufficient approximation to the trend of ground level concentrations, although data for such concentrations are not available for the U.K. as a whole, for the years before 1958.

To sum up, therefore, for urban areas in the U.K. smoke has decreased by rather more than 60 % since 1956. Of the smoke that still remains, at least 85 % arises from the domestic use of coal in open fires.

SMOKE—REGIONAL DISTRIBUTION

Although the position as described for the United Kingdom as a whole is eminently creditable, an examination of the smoke distribution over the country is more illuminating and points the way towards further progress. Using the Registrar General's statistical Regions, the distribution of smoke and sulphur concentrations for the year 1968/9 is given in table 2.

The entries are arranged in decreasing order of smoke concentration and the figures in column 3 show that in the towns in the south the smoke concentration is only one-third to one-half of the concentration in towns in the north. The reason for this is clear from column 2 which shows that the emission of smoke per person from domestic heating is greater in the north in about the same proportion. Only a small proportion of this can be accounted for by the extra amount of heat needed to maintain a house at a given temperature in the colder climate of the north, and it cannot be due simply to habit based on miners' concessionary coal, for the domestic coal consumption per head is very high in Northern Ireland even though all of it has to be imported and is therefore expensive. The reason is probably compensation for the uncomfortable conditions out of doors.

Table 2. Regional distribution of smoke and sulphur dioxide

region	domestic coal consumption per head of population/tonne	average concentrations 1968–9/μg m^{-3} smoke	sulphur dioxide
northwestern	0.61	109	147
northern	0.69	108	97
Yorkshire and Humberside	0.57	97	140
Scotland	0.45	88	87
Northern Ireland	0.63	79	96
East Midlands	0.53	77	102
West Midlands	0.45	63	119
East Anglia	0.33	51	87
Greater London	0.06	46	151
Southeastern, excl. London	0.17	39	78
Wales	0.62	39	62
Southwestern	0.23	33	68

In Wales, where a large proportion of the inhabitants live in the mining districts in the south of that country, the amount of coal burnt per head is as large as in the mining districts in the north of England, but the Welsh coal is a low-volatile coal and produces so little smoke that the South Wales towns have a lower smoke concentration than towns in any other region. The position of London is a little anomalous as the average concentration of 46 μg/m^3 is rather higher than would be expected from the very small emission per head of population. This is brought about by the very high population density compared with towns in the rest of the country. For example, in London the population densities of Southwark and Lambeth are 77000 and 57000/km^2 respectively, whereas in the northwest, the most heavily polluted region, the corresponding figures for Manchester and Salford, for example, are 24000 and 29000.

The remarkable changes that have occurred in smoke pollution in London since the Clean Air Act are shown in figure 3, where both emissions and observed concentrations are given. The latter have fallen from about 170 μg/m^3 in 1958 to 50 μg/m^3 in 1968.

Smoke—general conclusions

The medical verdict on smoke was given last year by Professor P. J. Lawther, Director of the Air Pollution Unit of the Medical Research Council who said that, 'in the present state of knowledge, smoke in any concentration was undesirable and could well constitute a hazard to health; it should be eliminated as far as was economically possible'. The last phrase leaves the question of the immediate objectives open, although the long-term aim must be the complete elimination of smoke. The present authors are impressed by the fact that towns in the south of England (leaving London out of consideration for the moment) are pleasant places to live in and that what little smoke remains in the air does not detract from their amenities, whereas, on the other hand, north of England towns which could otherwise be eminently satisfactory places to live in, are made vastly less attractive because of smoke which causes general murkiness, reduction of sunlight, poor vegetation and so on. They propose, therefore, to use the towns in the south of England as a yardstick against which to judge pollution in the rest of the country.

With regard to smoke, the data discussed in this paper have shown that pollution near ground level is almost entirely caused by smoke from domestic heating, and that, for the country as a whole, this is slowly but steadily decreasing. The National Survey data have also shown that, with the exception of a few separate districts in a few towns, smoke is uniformly satisfactorily low in the towns of the south but is still much higher and still unsatisfactory in the north. The question posed by this position is whether, with existing knowledge and legislation, the north can be made as free from smoke as the south. The answer is provided by the data presented above for London, which some ten years ago was as highly polluted by smoke as anywhere in the country. By the vigorous application of the domestic provisions of the Clean Air Act, and the changing social framework, the great housing estates of Outer London have been made as free from smoke

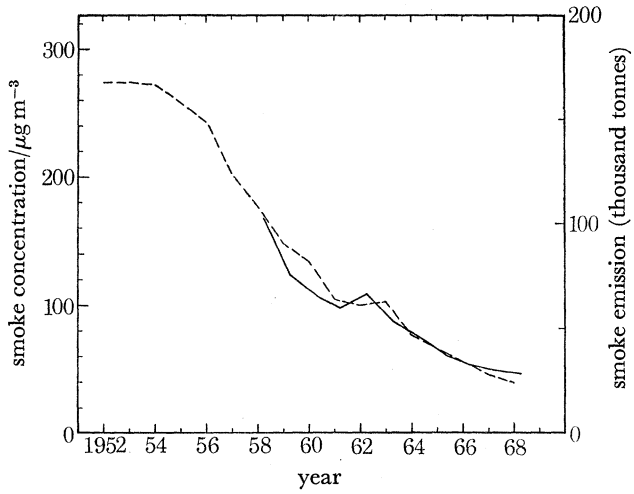

FIGURE 3. Smoke concentrations and emissions in London. ——, Average concentration; – – – –, emission.

as any urban areas in the south and the inner core of Central London is within striking distance of achieving the same state of cleanliness in spite of its very high population density. This is not something that can only be achieved in the south because the data for Sheffield, a great industrial town in the north, show the same spectacular progress. A word of warning about Inner London should however be inserted because its high population, concentrated within a ring of hills, makes it particularly susceptible to increased pollution when weather is unfavourable to its free dispersion. Efforts to bring the whole area under 'smoke control' under the Clean Air Act must not be relaxed if future episodes of dangerously high pollution are to be avoided.

SULPHUR DIOXIDE

Professor Lawther's statement on the medical effects of pollutants quoted above, continued as follows 'There was no evidence that reasonably low concentrations of sulphur dioxide were, of themselves, harmful, and if the concentrations of smoke were low he would be inclined to accept peak concentrations of up to 1000 $\mu g\ SO_2/m^3$, but would consider anything in excess of this to be potentially harmful, at least to some people'. This would mean aiming at a limit of some 100 to 150 $\mu g/m^3$ for the average winter concentration, or 75 to 100 $\mu g/m^3$ for the average annual concentration. At the concentrations at which it is present in air, sulphur dioxide presents no amenity problem.

The position with regard to pollution by sulphur dioxide in the United Kingdom is summed up by the data in tables 1 and 2, and by figures 4 to 6 which were prepared in a similar way to the corresponding graphs for smoke given in figures 1 to 3. The following details should be noted.

Figure 4 shows that the total emission of sulphur dioxide reached a maximum in 1963 and has declined by some 6 % since that date in spite of steadily increasing population and industrial activity. In accordance with the fuel policy outlined in the White Paper, this decline should continue, as indicated in figure 4, to 13 % by 1975. The reason for this is the increasing use of natural gas and nuclear energy. This places the United Kingdom in a very favourable position relative to the continent where no such decline in emissions of sulphur dioxide has occurred or is, indeed, expected.

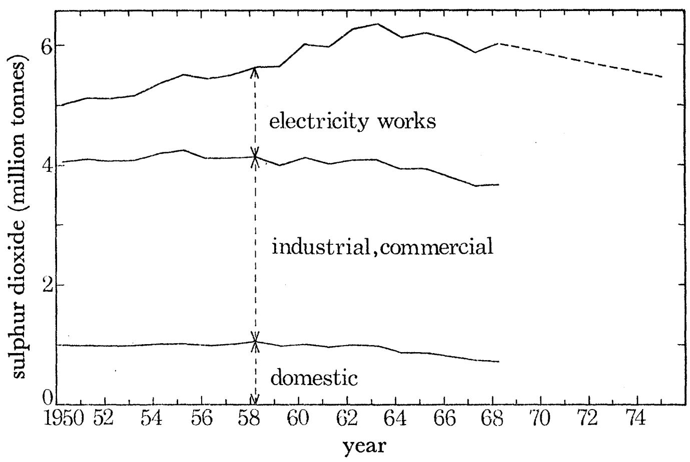

FIGURE 4. Emissions of sulphur dioxide in the United Kingdom. ——, Estimated from actual fuel consumption; – – – –, estimated from forecast fuel consumption.

It is also seen from figure 4 that for the period under review domestic emissions of sulphur dioxide have decreased by about 30 % and industrial emissions (including the heating of commercial premises but not including electricity works) by some 10 %.

The trend in observed concentrations of sulphur dioxide in the air for the United Kingdom is shown in figure 5, which shows a decrease of about one-third since 1960–1. This curve bears no relationship whatsoever to the total emissions in figure 4 which are dominated by the changing emissions from electricity works.

The satisfactory height of their chimneys, which have been deliberately designed to keep pollution at ground level to a minimum, and the siting of the large new stations well away from towns, has no doubt led to this satisfactory state of affairs. The decrease of ground-level concentration bears much more relationship to the changes in domestic emissions and suggests that, under normal circumstances, most of the sulphur dioxide found near ground level comes from domestic heating.

This is confirmed by an entirely independent argument as follows: if ground-level concentrations were determined solely by domestic emissions, the ratio of sulphur dioxide to smoke in the air would be the same as the ratio of these substances in domestic emissions, which is approximately unity. If, on the other hand, all emissions contributed to an equal degree, the ratio would be about 6 (see table 1). The average value observed for the National Survey sites is 1.5 (see table 2) which shows that industry, on the average, only makes a very modest contribution to

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ground-level concentrations of pollutants. This, again, is a measure of the success of the aerodynamicists and architects in designing chimneys in relation to buildings so as to reduce downdraught in the lee of the buildings to a satisfactory extent.

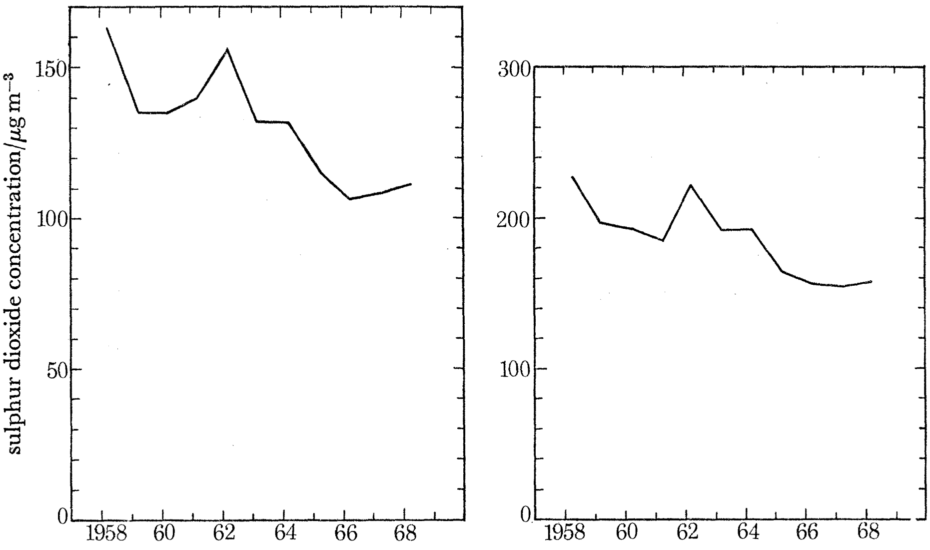

FIGURE 5 FIGURE 6

FIGURES 5 AND 6. Sulphur dioxide concentrations in (5) the U.K. and (6) London.

The regional distribution of sulphur dioxide, as given by table 2 differs from that of smoke in one important respect, namely, that London has as high an average sulphur dioxide concentration as the industrial north. This is partly due to the high population density commented on in connexion with the smoke data, but even more to the very high density of commercial premises in the central areas. Figure 6 shows that, even in London, there has been a decrease in sulphur dioxide concentration of about 25 % over the last ten years, but the concentration is still uncomfortably high and some limitation of the sulphur content of oils burnt in Inner London may well become necessary. This has already been done in Paris and has caused no great difficulty.

POLLUTION AND THE ARCHITECT AND TOWN PLANNER

The general pattern and trends in air pollution from the burning of fuels throughout the United Kingdom having been considered, the position may now be examined in relation to the activities of the architect and town planner. For this purpose it is convenient to divide urban areas into residential districts, industrial districts, commercial centres and busy streets.

Residential districts

From the analysis of the air pollution problems given above it is clear that practically all the pollution by smoke and much of the pollution by sulphur dioxide arises from domestic heating. There is no technical means of preventing smoke when coal is burnt on an open fire, nor of preventing pollution by sulphur dioxide when either coal or any solid smokeless fuel is burnt in this way. The town planner has helped in the past by reducing the density of modern housing compared with the congested housing of the last century which it is replacing, but that is not enough. It is suggested that in all instances where heating by gas, electricity or low-sulphur oil cannot be used, very serious consideration should be given to district heating. This requires a tall chimney for each such scheme, and to be aesthetically acceptable, the chimney must be suitably designed and concealed within a tower block. There are several such schemes in the United Kingdom and very many on the continent and in America. The question will be taken up again later in connexion with city centres.

Industry

The flow of air round buildings and the dispersion of chimney gases is sufficiently well understood in simple cases to enable chimneys to be designed in relation to the neighbouring buildings so that the chimney plumes do not become entrained in the turbulent wake of the buildings and the gases do not reach ground level before they are sufficiently diluted to cause little or no pollution problems. In more complicated cases, with buildings of difficult shapes or with difficult local topography, wind-tunnel tests will always be necessary to arrive at a satisfactory design. When the design has been fixed it will almost always be found that the chimney is of a height that is aesthetically unacceptable in any but a purely industrial zone. It is at that stage that the town planner must be firm in placing the factory concerned in such a zone. There should be no difficulty about chimney height in an industrial zone because arrays of industrial chimneys can be designed so as to be very satisfactory from a visual point of view. On the broader scale the architect or town planner can help reduce the effects of industrial effluents by judicial siting of the different types of area, residential, commercial, as well as industrial, taking into account the orography and/or local topography.

Town centres

The problem of pollution by sulphur dioxide in city centres is likely to remain a serious one because the fuel consumption per unit area is very high compared with a residential area. Moreover, the city centre is affected by the drift of pollution from the outskirts whatever the wind direction. The most elegant solution is provided by the Shell Centre in London where one heating plant serves a set of office blocks near a central tower block in which the chimney flue is concealed. The roof of the tower is a very flat pyramid with the chimney just protruding in the centre. The shape of the roof and the velocity of the gases in the flue were designed on wind-tunnel tests to prevent entrainment of the chimney plume in the wake of the tower. The result is that the whole complex is heated without causing air pollution in the vicinity and causing very little elsewhere.

Many modern tower blocks have short chimneys whose effluents are unlikely to get away cleanly except in calm conditions, and which could be expected to pollute the buildings themselves as well as neighbouring buildings. Pollution was measured on different floors and different faces of such a block in the Barbican, in the City of London, situated among similar buildings. For a given 3h period the concentrations found simultaneously at the different points varied by a factor of up to five or six, but over three winter months no particular floor or face had a higher average concentration or was more likely to have the highest peak concentration than the others (see figure 7*a* and *b*), except that smoke was rather lower at the top, presumably because smoke from diesel traffic is emitted at ground level. In particular the upper storeys were at no time grossly polluted, serious pollution being found only on the roof itself by the chimney, outside the penthouse windows.

The most difficult situations arise from the presence of buildings and chimneys of different heights in juxtaposition, situations that should never have been allowed to develop. A blatant and not uncommon example is that of tall modern buildings with their own boiler plant set some 50 m or so away, with a chimney half the height of the building. When the wind blows from the chimney to the building, the building itself is grossly polluted; with the wind in the opposite direction, the chimney plume is caught in the turbulent wake of the building and the whole neighbourhood is polluted.

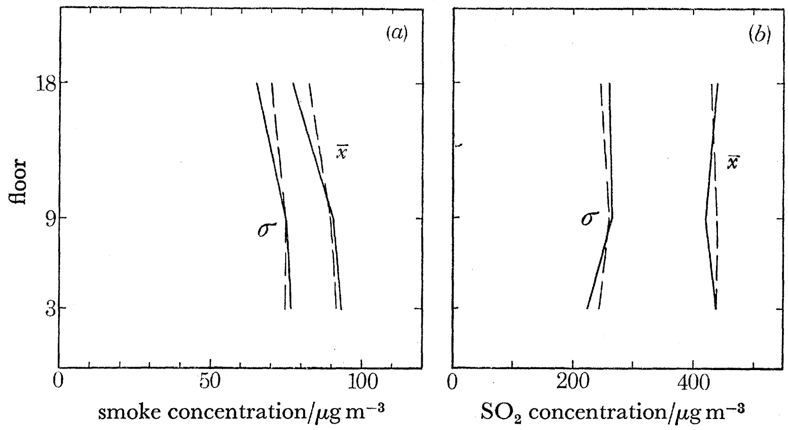

FIGURE 7. (*a*) smoke and (*b*) sulphur dioxide at different points of a twenty-storey building. ——, North face; — —, south face. $\bar{x}$ mean and σ standard deviation of (*a*) 475 and (*b*) 516 3 h observations.

Road traffic

Pollution by traffic is a local problem, because the total weight of pollutants emitted is small in comparison with that from chimneys. The contribution of traffic to background pollution is practically undetectable 50 m down a side street and also falls off rapidly above the street. On the other hand, the smokiest sites, i.e. those at which the soiling capacity of the suspended material is greatest in towns such as London, are now found, not in high density residential areas but on the busiest streets and squares, presumably because of diesel smoke. Workers in offices and shops near ground level in these streets are regularly exposed to this pollutant because smoke has a high penetrating capacity and tends to be found in almost as high concentrations inside buildings as outside, even in the absence of tobacco smoke. They will also be exposed to the other vehicle effluents, including carbon monoxide and, of course, noise. The modern practice of keeping traffic separate from pedestrians, shops and offices is therefore to be encouraged, as also is the movement away from the old narrow canyon-like streets which channelled the pollution, and prevented its rapid dispersion. In such streets the highest concentrations of traffic pollution are found on the leeward side because of the effect of the buildings and the pollution is noticeably higher where the street narrows.

There is evidence that traffic flow can affect chimney effluent dispersion. Workers in Sweden found pollution by both smoke and sulphur dioxide in a narrow one-way street in Gothenburg to be three to four times higher when there was heavy traffic than when there was little traffic. This could not be due solely to emissions from the vehicles; thus air contaminated with smoke and sulphur dioxide must have been drawn down to the street from chimney level.

The steady increase in the number of vehicles on the streets in recent years has not necessarily involved a corresponding increase in levels of pollution in streets. For the past decade the laboratory of the Préfecture de Police in Paris has carried out a systematic statistically designed survey of pollution by carbon monoxide in the streets and has found no increase in average or peak concentrations of this pollutant. This satisfactory finding is no doubt due to the measures which are progressively being adopted in this town, as in others, to keep traffic flowing, e.g. road widening, introduction of one-way systems, of ring roads and underpasses, and control of parking. The same workers have found very high concentrations of carbon monoxide in car parks. Underground and multi-storey car parks, underpasses and tunnels do of course present well-known ventilation problems. More unexpectedly pollution problems can also arise on bridges such as the Forth road bridge or the Sydney Harbour bridge on windy days, when concentrations in some of the toll-collectors' booths have been found to be unacceptably high, i.e. above the limit laid down for industrial premises.

Summarizing, there is unlikely to be any conflict between town planners and architects on the one hand, and those responsible for air quality on the other, as far as pollution by traffic is concerned in new towns or districts. The one obvious conflict of interests may lie between those concerned with noise abatement and the pollution control authorities, because noise from traffic can be confined by screening the road with walls or trees, or putting it in a cutting, and these will inhibit dispersion of pollutants. Problems do arise however when new roads are constructed in established districts. The pollution and loss of amenity suffered by the householder who finds himself with a major road a few feet from his front door or from his first-floor bedroom window have been well publicized. When the road passes at chimney level through an industrial area rather than a residential one, however, the position is reversed and the road maintenance authorities can find themselves with unexpectedly large bills for upkeep of the painted steelwork on the flyovers.

Conclusions

Air pollution by smoke is caused by obsolescent industry and, above all, by obsolescent domestic heating. As these are modernized smoke will disappear but the process must be accelerated by administrative action. The part of the town planner in this is to get rid of the open fire as a means of domestic heating.

Pollution by sulphur dioxide is rather less serious but its reduction by reducing emissions is very much more costly than the reduction of smoke. It is here that the architectural aerodynamicist as well as the town planner has a big part to play for ground-level concentrations can be reduced by proper dispersion of chimney effluents much more economically than by reducing the emissions.

The authors wish to thank Mrs B. Gooriah for preparing the trend data and for helpful discussion of them.