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Environmental Health Criteria 8

SULFUR OXIDES AND SUSPENDED PARTICULATE MATTER

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CONTENTS

While every effort has been made to present information in the criteria documents as accurately as possible without unduly delaying their publication, mistakes might have occurred and are likely to occur in the future. In the interest of all users of the environmental health criteria documents, readers are kindly requested to communicate any errors found to the Division of Environmental Health, World Health Organization, Geneva, Switzerland, in order that they may be included in corrigenda which will appear in subsequent volumes.

In addition, experts in any particular field dealt with in the criteria documents are kindly requested to make available to the WHO Secretariat any important published information that may have inadvertently been omitted and which may change the evaluation of health risks from exposure to the environmental agent under examination, so that the information may be considered in the event of updating and re-evaluation of the conclusions contained in the criteria documents.

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A WHO Task Group on Environmental Health Criteria for Sulfur Oxides and Suspended Particulate Matter met in Geneva from 6 to 12 January 1976. The meeting was opened by Dr B. H. Dieterich, Director, Division of Environmental Health, who welcomed the participants and the representatives of other international organizations on behalf of the Director-General. Dr Dieterich briefly outlined the history and purpose of the WHO Environmental Health Criteria Programme and the progress made in its implementation, thanks to the active collaboration of WHO Member States and the support of the United Nations Environment Programme (UNEP).

The Task Group reviewed and revised the second draft criteria document and made an evaluation of the health risks from exposure to these substances.

The first and second drafts were prepared by Professor B. G. Ferris, Jr, Harvard University School of Public Health, USA. The comments on which the second draft was based were received from the national focal points collaborating in the WHO Environmental Health Criteria Programme in Belgium, Bulgaria, Canada, Czechoslovakia, the Federal Republic of Germany, Greece, Japan, New Zealand, Poland, Sweden, USA, USSR and from the Food and Agriculture Organization of the United Nations (FAO), the United Nations Eduational Scientific and Cultural Organization (UNESCO), the United Nations Industrial Development Organization (UNIDO), the World Meteorological Organization (WMO), the International Atomic Energy Agency (IAEA), and the Commission of European Communities (CEC). Comments were also received from Professor H. Antweiler and Dr B. Prinz (Federal Republic of Germany), Professor K. Biersteker and Dr R. van der Lende (Netherlands), Professor F. Sawicki (Poland), and Professor W. W. Holland and Professor P. J. Lawther (United Kingdom).

The collaboration of these national institutions, international organizations and individual experts is gratefully acknowledged. The Secretariat also wishes to thank Professor B. G. Ferris, Jr and Mr R. E. Waller for their invaluable assistance in the final stages of the preparation of the document.

In view of the substantial amendments made to the document (particularly within sections 2 to 5) since the meeting of the Task Group, a revised version was circulated to all members in February 1978. At the same time, copies of a newly-produced review of the health effects of particulate pollution (Holland et al., in press), that had been submitted for consideration, were distributed to the members. Comments were sought on the draft of the criteria document itself, and on any amendments or additions considered necessary in

light of the new report. These comments, together with others received from the International Petroleum Industry Environmental Conservation Association, and the International Iron and Steel Institute, were then considered by a small group consisting of the Chairman of the Task Group meeting, the Rapporteur and some members of the Secretariat. The alterations suggested (mainly within section 9) were circulated again to the original members of the Task Group prior to publication.

The document has been based, primarily, on original publications listed in the reference section. However, several recent reviews of health aspects of sulfur oxides and suspended particulate matter have also been used including those by Katz (1969), Committee on the Challenges of Modern Society (1971), Organization for Economic Cooperation and Development (1965), Rall (1974), Task Group on Lung Dynamics (1966), Task Group on Metal Accumulation (1973), US Department of Health, Education and Welfare (1969a), US Environmental Protection Agency (1974), World Health Organization (1976a), and World Meteorological Organization (1974).

The purpose of this document is to review and evaluate available information on the biological effects of sulfur oxides and suspended particulate matter including suspended sulfates and sulfuric acid aerosols, and to provide a scientific basis for decisions aimed at the protection of human health from the adverse consequences of exposure to these substances in both occupational and general environments. Although there are various routes of exposure, such as inhalation, ingestion (World Health Organization, 1971, 1974) and contact with skin, attention in this report has been concentrated upon the effects of inhalation of these substances, since this is the most important route of exposure. The discussion has also been limited to sulfur dioxide, sulfur trioxide, sulfate ions, and particulate matter primarily resulting from the combustion of fossil fuels. The sulfate ion has been considered in the variety of forms in which it occurs in the atmosphere, e.g., sulfuric acid and various sulfate salts.

The vast literature on these pollutants has been carefully evaluated and selected according to its validity and relevance for assessing human exposure, for understanding the mechanisms of the biological action of the pollutants and for establishing environmental health criteria, i.e., exposure-effect/response relationships in man. Environmental considerations have been limited to elucidating the pathways leading from the natural and man-made sources of these substances to the sites of toxic action in the human organism. The non-human targets (plants, animals, ecosystems) have not been considered unless the effects of their contamination were judged to be of direct relevance to human health. For similar reasons, much of the published information on the effects of these pollutants on experimental animals has not been included.

Details concerning the WHO Environmental Health Criteria Programme

including some terms frequently used in the document may be found in the general introduction to the Environmental Health Criteria Programme published together with the environmental health criteria document on mercury (Environmental Health Criteria 1, Mercury, Geneva, World Health Organization, 1976), now also available as a reprint.

The following conversion factors have been used in the present document:[a]

Sulfur dioxide	1 ppm = 2856 $\mu g/m^3$
Ozone	1 ppm = 2140 $\mu g/m^3$
Carbon monoxide	1 ppm = 1250 $\mu g/m^3$

1. SUMMARY AND RECOMMENDATIONS FOR FURTHER RESEARCH AND ACTION

1.1 Summary

1.1.1. Chemistry and analytical methods

Procedures in common use for the sampling and determination of sulfur dioxide, sulfates, sulfuric acid, and suspended particulate matter have been discussed, noting their limitations and stressing the need to specify the method of measurement when quoting results in relation to studies on the effects of health.

Several alternative methods, already in common use, can be recommended for the determination of sulfur dioxide using manually operated sampling and, providing the extent of interference from other pollutants is taken into account, results are reasonably comparable with one other. A wide range of continuous automatic instruments is available and, where the expense is justified, they can provide additional information on short-term variations in concentrations[b] of sulfur dioxide.

Methods for the determination of particulate sulfate do not present any special problems, but, at present, there does not appear to be any wholly satisfactory way of determining sulfuric acid separately from sulfates and other interrelated components.

Much attention was given by the Task Group to the sampling and determination of suspended particulate matter, stressing that this was not a well-defined entity, and that it could only be assessed in terms of certain physical

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[a] When converting values expressed in ppm to $\mu g/m^3$, the numbers have been rounded up to 2 or, exceptionally, 3 significant figures, and concentrations higher than 10 000 $\mu g/m^3$ have been expressed in mg/m^3.

[b] Throughout the document, the word "concentration" refers to mass concentration unless otherwise stated.

properties. The several methods in common use are based on different characteristics, and the Task Group felt that clear distinctions should be made between them, particularly in relation to those based on blackness (the "smoke" measurements commonly made in Europe) and those based on weight (the total suspended particulate matter commonly measured in USA). The need to limit the measurements to particles within the respiratory size range, and to consider the wide range in chemical composition of the samples was also stressed.

1.1.2 Sources of sulfur oxides and particulate matter

Despite the fact that some sulfur oxides and particulate matter occur naturally in air in large amounts, contributions from man's activities are generally of prime importance in urban areas. In particular, the combustion of fuels for heating and power generation is considered responsible for most of the sulfur dioxide and particulate pollution to which the general population is exposed. The three broad categories of sources are: domestic sources associated with the use of coal and some other fuels for heating and cooking; industrial sources; and motor vehicles. Domestic and motor vehicle sources have a disproportionate effect on concentrations in the immediate vicinity, because the pollution is emitted close to ground level.

1.1.3 Dispersion and environmental transformations

The temperature of the gases, the efflux velocity, and the height of the chimney are important factors in securing effective dispersion of emissions from combustion sources. The topography of the surrounding area and meteorological factors determine the extent to which these pollutants are dispersed and diluted to tolerable levels. Temperature inversion can trap emissions over urban areas to produce concentrations up to several hundred times the normal values.

Several processes, including photochemical reactions in the presence of hydrocarbons, catalytic oxidation in the presence of particulate matter containing iron or manganese compounds, and reaction with ammonia, leading to the transformation of sulfur dioxide to sulfates or sulfuric acid, are involved in the atmospheric reactions of sulfur dioxide and suspended particulate matter. The relative importance of each of these is not well established, but together they account for the gradual removal of most of the sulfur dioxide dispersed into the air, the remainder being deposited directly on soil, water, vegetation, or other surfaces.

1.1.4 Environmental concentrations and exposures

Sulfur dioxide and suspended particulate matter are measured routinely in

many areas throughout the world, but care is needed to ensure that observations from monitoring networks set up for other purposes are suitable for assessing risks to health. The location of samplers in relation to sources, the surrounding topography, and the population at risk need to be considered, and also the time-resolution of the observations. Averaging periods of 24 h are commonly used in relation to short-term exposures, though, in some circumstances, still shorter periods are required. For long-term exposures, annual means based on a series of daily observations may be adequate.

Examination of concentrations of sulfur dioxide and suspended particulate matter in the air of a number of cities throughout the world has revealed a wide range in annual mean values and an even wider range of peak values, reflecting the effects of climatic factors and liability to temperature inversions. The typical, annual, arithmetic mean concentrations of sulfur dioxide in urban areas range from 100-200 $\mu g/m^3$ (0.035-0.07 ppm) with the highest daily means from 300-900 $\mu g/m^3$ (0.1-0.3 ppm). For smoke, the corresponding values are 30-200 $\mu g/m^3$ and 150-900 $\mu g/m^3$ respectively, and for suspended particulate matter, measured by the high volume sampler, the annual arithmetic means are 60-500 $\mu g/m^3$ with maximum daily means of about 150-1000 $\mu g/m^3$. Relatively little information is available on sulfates but some data have been obtained in the USA.

Indoor concentrations of these pollutants also deserve attention. In the absence of specific sources of sulfur dioxide or particulate matter, concentrations are generally lower indoors than outdoors. Proposals for assessing weekly-weighted average exposures of people in terms of the proportion of time spent in various locations were discussed.

Industrial situations in which high concentrations of sulfur dioxide or sulfuric acid occur should be carefully assessed in each specific case, but it should be noted that industrial dusts are generally very different in character from the suspended particulate matter in urban air.

1.1.5 Absorption, distribution, and elimination

Although the major route of absorption of the relevant sulfur compounds and particulate matter into the body is through the intestinal tract, the respiratory tract is the most vulnerable area for airborne materials.

Most studies on both man and animals have indicated that 40 to 90% or more of inhaled sulfur dioxide is absorbed in the upper respiratory tract. Taken into the blood stream, it appears to be widely distributed throughout the body, metabolized, and excreted via the urinary tract.

The deposition pattern of particulate matter varies with particle size, shape, and density, and also with airflow conditions. Deposited particles are largely phagocytized and transported to the mucociliary escalator, into the

interstitium, or to the lymphatic system. The biological half-times range from days to years depending on their chemical composition.

Soluble particles may dissolve in the mucous or aqueous lining of the lungs. In the first case, they will be eliminated via the mucociliary route. In the second, they may diffuse into the lymph or blood.

1.1.6 Effects on experimental animals

Selected studies on animals that involve both short-term (24-h or less) and long-term (more than 24-h) exposures have been reviewed in this document; certain interactions between the effects of sulfur oxides, particulate matter, and other air contaminants have also been reported. The lowest, adverse-effect concentrations vary considerably from study to study. The discrepancies may be due to differences in the sensitivity of the test animals used or in exposure conditions including the duration of exposure and the pattern of exposure (single, continuous, repeated, or intermittent). Furthermore, exposure may have been to a single pollutant or to a mixture of various agents, or different effects may have been analysed.

In general, however, it has been noted that sulfuric acid aerosols and some sulfate salts such as zinc ammonium sulfate are more irritating to respiratory organs than sulfur dioxide, and that some aerosols, particularly those in the submicron size range, enhance the effect of sulfur dioxide when they are present simultaneously.

Caution must be exercised in light of the fact that differences in metabolism and life span make extrapolation of results of animal experiments to man difficult. However, some of these studies have indicated possible mechanisms of biological action on the respiratory system – e.g., interference with mechanisms for the clearance of bacteria and inert particles from the lung.

1.1.7 Effects on man

1.1.7.1 *Controlled exposures*

Inhalation studies on human volunteers have been performed under controlled, short-term exposure conditions with sulfur dioxide or sulfuric acid mist singly or in combination, or with mixtures of these and other compounds. Some of these studies have proved useful for developing exposure-effect relationships.

When exposed to sulfur dioxide alone, slight effects on respiratory function were demonstrated at a concentration of 2.1 mg/m^3 (0.75 ppm) but not at 1.1 mg/m^3 (0.37 ppm), while sulfuric acid mist affected respiratory function at levels as low as 0.35 mg/m^3. Synergistic effects on pulmonary function were reported from joint exposure to sulfur dioxide and hydrogen

peroxide as well as sulfur dioxide and ozone.

The effects of sulfuric acid mist and sulfur dioxide on sensory receptors and cerebral cortical function have been studied extensively in the USSR. In these reflex actions, threshold levels for sulfuric acid were always much lower than those for sulfur dioxide. Synergistic effects of these compounds have also been noted.

1.1.7.2 *Industrial exposure*

Effects of exposure to sulfur dioxide, particulate matter, or sulfuric acid mist have been studied in workers in refrigerator manufacturing plants, steel mills, paper and pulp mills, and in the battery industries.

Although the exposure levels were very high (daily mean concentrations of sulfur dioxide of up to 70 mg/m^3 or 25 ppm) in some studies, no significant differences in effects were found when compared with the controls. In another study, effects on respiratory function were not detected with joint exposure to sulfur dioxide and suspended particulate matter at mean concentrations over 3 years of 1.8 to 2.1 mg/m^3 (0.6-0.7 ppm) and 600 to 1800 μg/m^3, respectively.

Exposure to sulfuric acid mist produced effects (nose and throat irritation) at a concentration of 2.0 mg/m^3, while exposure to a concentration of 1.4 mg/m^3 did not affect pulmonary function. However, the effects of this pollutant are also closely dependent on particle size.

1.1.7.3 *Community exposure*

The large amount of literature on the effects of community exposure has been reviewed and detailed consideration has been given to those studies that appeared to have adequate data and design, in particular, due control for cigarette smoking and satisfactory measurements of exposure levels. Certain of these studies were selected to develop exposure-effect relationships. In the evaluation of the studies it became apparent that it was not possible to compare two fundamentally different methods of measuring exposure to particulate matter -- one measuring black smoke and the other measuring total suspended particulates, usually by the high-volume sampling method.

Studies have been performed in terms of both short and long-term exposures and in relation to changes in the incidences of mortality and morbidity. In morbidity studies concerned with short-term exposure to a combination of sulfur dioxide and total particulates, the lowest concentrations (24-h mean) at which adverse effects were noted were 200 μg/m^3 (0.07 ppm) and 150 μg/m^3 (high volume sampler), respectively. In long-term, joint exposure studies, effects were noted at annual mean concentrations of 60-140 μg/m^3 (0.02-0.05 ppm) for sulfur dioxide and 100-200 μg/m^3

for total suspended particulates (light-scattering method). However, there were reservations about the validity of some of these studies.

Increases in mortality were reported in relation to episodes of high pollution with 24-h mean concentrations of the order of 500 $\mu g/m^3$ (0.18 ppm) for sulfur dioxide and 500 $\mu g/m^3$ for smoke.

The question as to whether carcinogenic components of suspended particulate matter, such as benzo(a)pyrene may have some influence on the incidence of lung cancer was not discussed by the Task Group. [a]

1.1.8 Evaluation of health risks

From a critical evaluation of the studies on the health effects of community exposures, the Task Group developed two summary tables; one for the expected effects on the health of selected populations of short-term exposures to sulfur dioxide and smoke; the other for the effects of long-term exposures to these substances.

As an estimate of the lowest adverse-effect levels for short-term exposures, the Group selected the 24-h mean concentrations of 500 $\mu g/m^3$ (0.18 ppm) for sulfur dioxide and 500 $\mu g/m^3$ for smoke, as levels at which excess mortality might be expected among elderly people or patients with pulmonary diseases, and a sulfur dioxide concentration of 250 $\mu g/m^3$ (0.09 ppm) and a smoke concentration of 250 $\mu g/m^3$ as levels at which the conditions of patients with respiratory disease might become worse.

For long-term exposures, annual mean concentrations of 100 $\mu g/m^3$ (0.035 ppm) for sulfur dioxide and 100 $\mu g/m^3$ for smoke were selected as the lowest concentrations at which adverse health effects such as increases in respiratory symptoms, or respiratory disease incidence in the general population might be expected.

Based on these evaluations, guidelines for the protection of the health of the public were developed in terms of 24-h values (100 – 150 $\mu g/m^3$ for sulfur dioxide, and for smoke) and in terms of annual means (40 – 60 $\mu g/m^3$ for sulfur dioxide, and for smoke). In view of the limited amount of data available in relation to total suspended particulates, firm guidelines could not be recommended, but it was suggested that interim guidelines might be of the order of 60 – 90 $\mu g/m^3$ for annual arithmetic means and 150 – 230 $\mu g/m^3$ for 24-h values. Guidelines were not developed for sulfuric acid or sulfates, also because of lack of data.

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[a] Since the Task Group meeting, an International Symposium on Air Pollution and Cancer has been held at the Karolinska Institute, Stockholm, with the collaboration of the World Health Organization. One of the conclusions quoted in the report (Task Group on Air Pollution and Cancer, 1978) is as follows: "Combustion products of fossil fuels in ambient air, probably acting together with cigarette smoke, have been responsible for cases of lung cancer in large urban areas, the numbers produced being of the order of 5-10 cases per 100 000 males per year. The actual rate will vary from place to place and from time to time, depending on local conditions over the previous few decades."

1.2 Recommendations for Further Research and Action

(*a*) As most of the knowledge of effects discussed in this document relates to combinations of sulfur oxides with smoke, and as these pollutants are not wholly representative of the current exposure situation in a number of communities, there is a need to carry out epidemiological studies where possible effects can be related to particulate pollutants of other types, including sulfuric acid and sulfates, and to other gaseous components of the mixture.

(*b*) As epidemiological studies are still being carried out that do not take other variables, particularly smoking, into account when considering effects, and in which the exposure to pollution is not adequately assessed, it is recommended that the World Health Organization should provide guidance and advice on the minimum requirements for such studies.

(*c*) As a consequence of the conclusions reached on the expected effects on health of sulfur oxides, smoke, and total suspended particulates, and on the related guidelines for the protection of public health, it is recommended that existing monitoring practices should be reviewed and, if necessary, appropriately modified. To assist regulatory agencies in this respect, it is recommended that the World Health Organization should undertake consultations with environmental scientists, inhalation toxicologists, and epidemiologists to consider both the epidemiological and control aspects of the problem.

(*d*) As there is little information from occupational exposures that can be used for exposure-effect evaluations, it is recommended that such studies should be carried out particularly in relation to sulfur dioxide and related pollutants. These studies should include measurements of pollution over complete working shifts, taking into account variations with space and time over shorter periods, and exposures outside the working environment. The importance of following up people who may have left work because of effects on their health must also be stressed.

(*e*) The Group did not carry out a thorough evaluation of any possible association between lung cancer and air pollution. It is recommended that a separate evaluation should be carried out.

(*f*) As deposition and clearance of particles from the respiratory system is of fundamental importance for evaluating risks, and for the design of measuring instruments for use in monitoring systems, it is recommended that a thorough review of the relevance of existing information on the mixture of pollutants present in the ambient air be carried out, taking into account particle size distribution and chemical composition.

(*g*) Some laboratory experiments on the effects of sulfur oxides, smoke, and total suspended particulates do not need to be repeated, but the Task

Group considered that it was necessary for more experimental work to be carried out on the mechanism of the biological action of these pollutants and of their interactions with other agents.

(*h*) The Task Group found that information concerning the nature and effects of pollution had considerably increased since the WHO meeting on air quality criteria and guides in 1972, and that this had resulted in a somewhat different approach to the preparation of criteria for sulfur oxides and suspended particulate matter and to the recommendations for future action. It was considered, therefore, that the criteria should be reviewed at least every five years to take into account any new data on effects that may become available and the implications of any further changes in the character of pollution.

(*i*) Since observations on sulfur oxides, smoke, and total suspended particulates are considered mainly as indices of the complex mixture of pollutants in the ambient air, the Task Group recommended that, in addition to the continuation of efforts to reduce these pollutants, efforts should be made to control other pollutants.

2. CHEMISTRY AND ANALYTICAL METHODS

2.1 Chemical and Physical Properties

2.1.1 Sulfur oxides

Sulfur dioxide is a colourless gas that can be detected by taste by most people at concentrations in the range of 1000 to 3000 $\mu g/m^3$ (0.35-1.05 ppm). At higher concentrations (above about 10 000 $\mu g/m^3$; 3.5 ppm), it has a pungent, irritating odour. It dissolves readily in water to form sulfurous acid (H_2SO_3), and in pure solutions this is slowly oxidized to sulfuric acid by the oxygen from the air. In the presence of catalysing impurities such as manganese or iron salts, it is more rapidly converted (Freiberg, 1975, Johnstone & Coughanowr, 1958). Sulfur dioxide can also react either catalytically or photochemically in the gas phase with other air pollutants to form sulfur trioxide, sulfuric acid, and sulfates (see section 4).

Sulfur trioxide (SO_3) is a highly reactive gas, and, in the presence of moisture in the air, it is rapidly hydrated to sulfuric acid. In the air, therefore, it is sulfuric acid in the form of an aerosol that is found rather than sulfur trioxide, and, in general, it is associated with other pollutants in droplets or solid particles extending over a wide range of sizes (Waller, 1963). It can be emitted into the atmosphere directly, or may result from the various reactions

mentioned earlier. Sulfuric acid may also be formed from the oxidation of hydrogen sulfide in the air. The acid is strongly hygroscopic, and droplets containing it readily take up further moisture from the air until they are in equilibrium with their surroundings. If there is any ammonia present, it will rapidly react with sulfuric acid to form ammonium sulfate, which will continue to exist as an aerosol (in droplet or crystalline form, depending on the relative humidity). The sulfuric acid may react further with compounds in the air to produce other sulfates. Some sulfate reaches the air directly, from combustion sources or industrial emissions, and, in the proximity of oceans, magnesium sulfate is present in the aerosol generated from ocean spray.

A wide range of sulfur compounds is represented in the complex mixture of urban air pollutants, but, from a practical point of view, only the gas sulfur dioxide, and sulfuric acid and sulfates as components of the suspended particulate matter need be considered.

2.1.2 Suspended particulate matter

The term suspended particulate matter covers a wide range of finely divided solids or liquids that may be dispersed into the air from combustion processes, industrial activities, or natural sources, as discussed further in section 3. The composition of this material is dependent upon the types of sources contributing to it, and the broad definition is in terms of the settling velocity of the particles. For ideal spherical particles, the velocity can be predicted from Stokes' Law (Fuchs, 1964, see Table 1).

Table 1. Settling velocities of spherical particles of unit density in still air

	Diameter μm	Settling velocity, ms^{-1}
Suspended particulate matter	0.1	8×10^{-7}
	1.0	4×10^{-5}
	10	3×10^{-3}
	100	0.25
Deposited matter	1000	3.9

In the size range under about 10 μm, the settling velocity is negligible compared with the movement produced by wind and air turbulence, and such particles are liable to remain in suspension for periods of the order of hours or days, until they are removed by impaction or diffusion on to surfaces or are scavenged by rain. It is these particles, with diameters ranging from

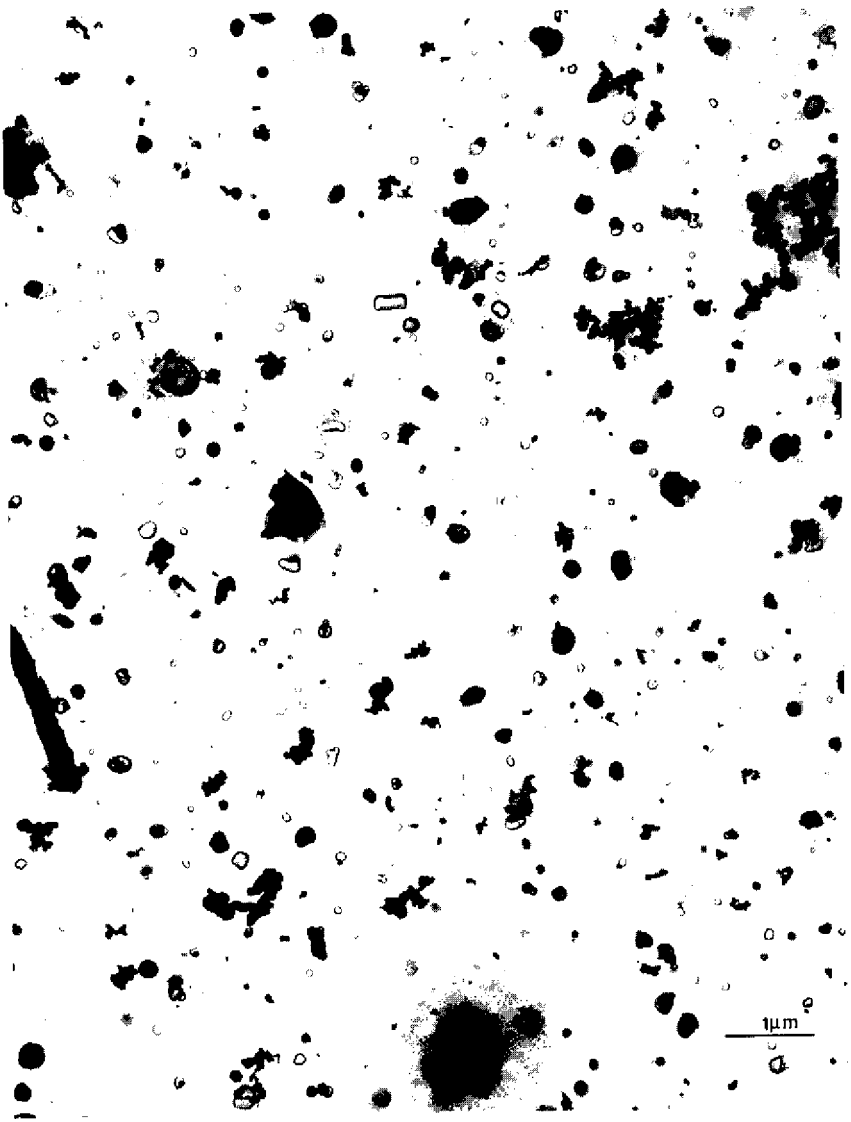

Fig. 1. Electron micrograph of particles from London air. Thermal precipitator sample, mixed pollution. Note: the magnification in this print is x 13 000 (From Waller et al., 1963).

well below 0.1 μm, up to about 5 to 10 μm, that are referred to as suspended particulates, but there is clearly no sharp dividing line between them and the larger particles of deposited matter (or "dustfall") that are liable to fall out rapidly, close to their source.

The suspended particulates are important in relation to health not only because they persist in the atmosphere longer than larger particles, but also because they are small enough to be inhaled and to penetrate deeply into the respiratory tract, as discussed in section 6. They are also responsible for reduction in visibility, and take part in reactions with other air pollutants.

Many of the particles in the air have complex shapes, as illustrated in the electron micrograph (Fig. 1). Among the particles shown are a number of "smoke aggregates", typical of the incomplete combustion of hydrocarbon fuels, consisting of small spherical particles of carbon or higher hydrocarbons having diameters of the order of 0.05 μm, clustered together in loose structures with overall diameters up to several micrometres. From the point of view of their behaviour during sampling or inhalation, such particles are classified in terms of their equivalent aerodynamic diameters, i.e., the diameters of unit density spheres having the same settling velocities. Some truly spherical material may be present, mainly as aqueous droplets containing dissolved salts, sulfuric acid, or occluded solid particles. These cannot be examined directly under the electron microscope, since the aqueous component evaporates completely, but some residues can be seen in Fig. 1, and the rings of small droplets indicate the presence of sulfuric acid (Waller et al., 1963). Many other types of particles, including small flakes and fibres can be seen in Fig. 1, and a wide range of sizes, shapes, and densities is commonly seen in all samples of suspended particulates in urban areas. For routine monitoring purposes, it is clearly out of the question to characterize the material completely in terms of size distribution and composition, but it is important to recognize that the suspended particulates generally comprise a heterogenous mixture, that can differ greatly in its characteristics from one location to another, and even from one occasion to another at any one site.

Estimates of size distribution can be obtained from electron micrographs by considering the particles compressed into equivalent spheres. The results are commonly plotted as cumulative frequency curves, and Fig. 2 shows results for a sample consisting largely of smoke aggregates. In this the mass median diameter (MMD) is approximately 1 μm, i.e., half the mass of material collected is contained in particles having effective (aerodynamic) diameters under one micrometer.[a]

[a] For further details concerning the definition of poly-dispersed aerosols containing particles of irregular shape see, for example, Fuchs (1964) or Task Group on Lung Dynamics (1966).

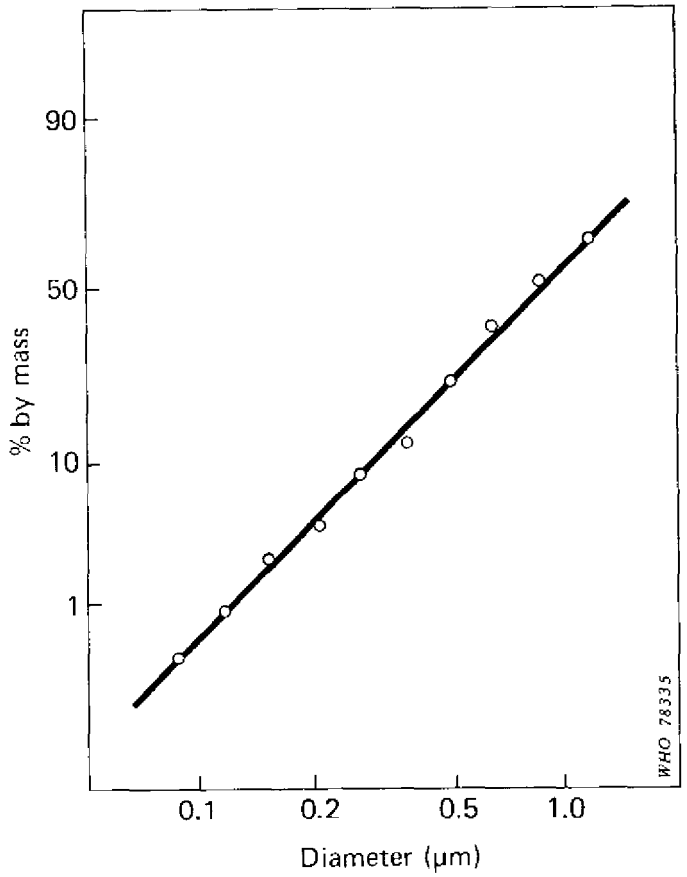

Fig. 2. Mass distribution of particles from London air (sampled close to traffic, and dominated by diesel smoke). Log-probability cumulative frequency plot (From: Waller, 1967).

The results shown in Fig. 2 indicate a log-normal distribution of particle size in that specific sample, but Willeke & Whitby (1975) have shown that distributions are often multimodal. These authors also stressed the importance of examining the distribution in terms of numbers of particles, and surface area, in addition to volume (or mass), for each curve may reveal features not shown by the others. An example of results obtained with their Minnesota Aerosol Analyzing System is shown in Fig. 3. This shows a mode in the volume distribution in the range 0.1 to 1 μm that is related to particles formed by coagulation or condensation from smaller units, and a further mode of

the order of 10 μm that corresponds with mechanically-produced particles, some of which are large enough to settle rapidly, and are not, therefore, strictly part of the suspended particulates.

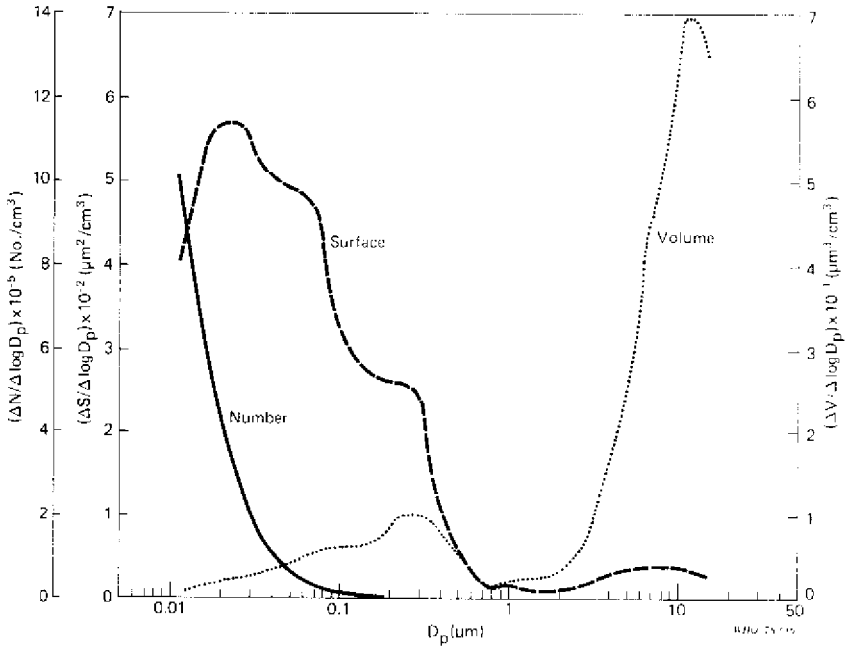

Fig. 3. Normalized frequency plots of number, surface, and volume distributions for average of series of particle size measurements on suspended material in urban air, Denver (From: Willeke & Whitby, 1975).

The impression gained of size distributions will, however, always depend on the characteristics of the instruments used. The most extensive series of results that has been reported was based on a modified Andersen cascade impactor (Lee & Goranson, 1972). This allows samples to be collected in five, roughly size-graded fractions, with a back-up filter as a sixth stage to collect the finest particles. Mass median diameters have generally been found to be below 1 μm in samples collected in urban areas of the USA, but this method cannot describe the size distribution as completely as that of Willeke & Whitby (1975).

Although it is possible to investigate the composition of individual particles to a certain extent, data on chemical composition are usually derived from larger samples as collected for the determination of the total mass of suspended particulates. Among the principal components are carbon, tarry material (hydrocarbons, soluble in organic solvents such as benzene), water

soluble material (such as ammonium sulfate), and insoluble ash (containing small amounts of iron, lead, and a wide variety of other elements).

The proportions of these components vary widely, depending on the types of sources in the locality. For example, the special feature of the suspended particulate matter in the United Kingdom prior to the implementation of the Clean Air Act was their high tar content, and this was particularly evident in high pollution episodes (Table 2).

Table 2. Examples of analyses of suspended particulates sampled in London prior to smoke control (high volume samples) [a]

	Typical summer sample (July 1955)	Typical winter sample (February 1955)	High pollution episode (January 1956)
Total suspended particulates ($\mu g/m^3$)	97	485	5111
Components as % of total:			
Organic (tar)	7.5	19.1	45.7
Sulfate	11.3	9.0	5.8
Chloride	0.8	0.2	1.0
Nitrate	0.8	0.5	0.7
Iron	1.3	1.4	0.1
Lead	0.7	0.4	0.1
Zinc	0.5	0.2	0.8

[a] From: The Medical Research Council Air Pollution Unit, now, Clinical Section of Medical Research Council Toxicology Unit (unpublished data)

Results from the extensive series of analyses of high volume samples of suspended particulate matter at sites in the USA indicate organic contents of the order of 10% of the total particulates (US Environmental Protection Agency, 1974a). Although little is known of the influence of the composition of the suspended particulate matter on effects on health, detailed analyses can be of value in identifying sources and are relevant in the study of reactions between pollutants. Thus iron and manganese, although only trace constituents, may be of importance in catalysing the oxidation of sulfur dioxide to sulfuric acid or sulfates. The lead content is usually related to pollution from motor vehicles, and traces of vanadium that are present come mainly from the combustion of residual oils. There may also be a variety of substances from noncombustion sources, such as road dust, material from the degradation of tyres, windblown soil, pollen, and emissions from industrial processes such as cement manufacturing or steel making.

The most important distinction to be made in relation to suspended particulate matter at the present time, however, is neither the precise size distribution, nor the detailed chemical composition, but the very broad characterization that results from the different methods of assessment that are in common use for routine monitoring purposes. These are discussed further in section 2.2.3. In subsequent sections, the term "smoke" has been used for observations of suspended particulate matter based on its soiling properties, and "total suspended particulates" for those based directly on weight. Since the former is mainly influenced by incomplete combustion products from the burning of fossil fuels, and is little affected by white or colourless materials such as ammonium sulfate, it is clear that the two terms are not interchangeable.

2.2 Methods of Sampling and Analysis

In general, the outdoor air has been sampled for sulfur oxides and suspended particulate matter in relation to community exposures, whereas indoor environments have been examined in connection with occupational exposures.

The most commonly used methods have been described in detail in a recently published manual (World Health Organization, 1976a) and their application in monitoring networks has been discussed in a further publication (World Health Organization, 1977). However, the bases of these and some other methods, that have been used in reporting concentrations of sulfur oxides and suspended particulates in the air, are discussed below to provide a better understanding of the measurements cited in epidemiological studies. It is important to ensure that any measurements that are made are supervised by someone competent in the field of air pollution monitoring, and the methods used must be reported together with the results.

2.2.1 Sulfur dioxide

If sulfur dioxide were the only contaminant of the air and providing the samples were of adequate size, each of the methods mentioned in Table 3 would give comparable results, indicating the true amount of sulfur dioxide. In normal urban environments, however, other pollutants are always present and although the sampling procedure can be arranged to minimize interference from particulate matter by filtering the air first, errors can still arise due to the presence of various gases and vapours. The choice of method depends on many factors, including the averaging time required: 24-h sampling periods are commonly used, and many of the methods are suitable for this. For shorter periods the choice is more limited, and for detailed information on short-term variations in concentration, instrumental methods are required.

Table 3. Methods of analysis for sulfur dioxide [a]

Method	Principle	Comment
Pararosaniline method [b]	Absorption of sulfur dioxide in solution of potassium tetrachloromercurate (TCM); complex formed reacts with pararosaniline and formaldehyde to produce a red-purple colour, determined colorimetrically (West & Gaeke, 1956).	Uses simple apparatus, and suitable for sampling periods ranging from 30 min to 24 h; samples should be analysed soon after collection; specific for sulfur dioxide, and possible interference from oxides of nitrogen and some metals can be eliminated (Pate et al., 1965; Scaringelli et al., 1967) Widely used in USA.
Acidimetric method [b]	Simple apparatus, often combined with smoke filter (see the Organization for Economic Cooperation and Development filter soiling method in Table 5); suitable for sampling periods of 24-h, or less in some circumstances (e.g. high pollution episodes, or occupational environments).	Absorption of sulfur dioxide in dilute hydrogen peroxide solution; the sulfuric acid formed is titrated against standard alkali (Organization for Economic Cooperation and Development, 1965).
Conductivity measurements	Sulfur dioxide is sampled in deionized water containing hydrogen peroxide where it is oxidized to sulfuric acid, as in the acidimetric method, increase in conductivity measured with a conductivity bridge (Adams et al., 1971).	Simple apparatus, suitable for sampling periods of the order of 24-h, usually combined with a filter to remove particulate matter; less reliable than acidimetric method, and not widely used in manual form, but the principle often used in automatic instruments (Derrett & Brown, 1978), applicable also to simple portable instruments for spot checks in urban or industrial environments (Nash, 1964), and to personal samplers for assessing occupational exposures (Sherwood, 1969).
Detector tube measurements	Air is drawn through tubes containing silica gel impregnated with indicator sensitive to sulfur dioxide; concentration assessed from the length of the stain (Ash & Lynch, 1972).	Portable, and no power supply required. Widely used for spot checks in occupational environments, or in other situations where the concentrations may be high (from about 3000 $\mu g/m^3$ upwards).
Iodine method	Sulfur dioxide absorbed in a solution of iodine contained in a wash bottle with a fritted bubbler, and solution titrated with thiosulfate (Elkins, 1959).	Applicable to occupational environments, but not now widely used; the method has been modified for colorimetric assessment, providing a basis for portable instruments for survey use (Cummings & Redfearn, 1957).
Automatic instruments	Based on conductivity, colorimetry, coulometry flame photometry, or gas chromatography (Hollowell et al., 1973).	Particularly valuable for following short-term variations in concentration, but difficult to assess 24-h average concentrations, unless linked with data processing equipment; instruments expensive, and must be under the control of experienced operators.
Sulfation rate	Sulfur compounds in the air react with an exposed cylinder or plate covered with a paste containing lead peroxide; sulfate formed is determined by precipitation with barium chloride (British Standards Institution, 1969a).	Simple and requires no power supply; sampling period long (30 days); results expressed in SO_3 /100cm^2/day, indicating rate of reaction of sulfur compounds with surfaces; not specific for sulfur dioxide, does not indicate concentrations in the air, and although often quoted in epidemiological studies, of little value for these.

[a] From: Pate et al., (1965)
[b] Methods that are described fully in the manual of the World Health Organization (1976a).

In occupational environments, the mixture of air pollutants may be simple and more clearly defined than that in urban air. Sulfur dioxide may be emitted from a specific process rather than from a variety of combustion sources, and the air may then be relatively free from interfering gases. Concentrations may also be much higher than those encountered in urban air, allowing short sampling periods to be used, and, since concentrations are liable to change rapidly, this may even be essential. Also, concentrations may vary greatly over short distances, depending on the proximity of the source of pollution; this makes the assessment of exposure based on measurements at fixed sites difficult. There may be a preference in these circumstances for methods suitable for use with portable instruments.

2.2.2 Suspended sulfates and sulfuric acid

Most of the methods mentioned in Table 4 assess the total water-soluble sulfates collected on filters as part of the suspended particulates. In general, any sulfuric acid present is included with this, and some of the material present as acid in the air may be converted to neutral sulfate on the filter during sampling. There is no completely satisfactory method for the determination of sulfuric acid in the presence of other pollutants, but some procedures for examining the acidic properties of suspended particulates have been referred to. There is an urgent need for more research in this field. No methods, other than those mentioned in Table 4, are, as yet, sufficiently well established for widespread application in epidemiological studies, but much research work is in progress.

Table 4. Methods of analysis for suspended sulfates and sulfuric acid

Method	Principle	Comment
Turbidimetric method	Sample collected on sulfate-free glass fibre or other efficient filter; sulfate extracted and precipitated with barium chloride, measuring the turbidity of the suspension spectrophotometrically (US Environmental Protection Agency, 1974b).	Samples normally collected over 24-h periods by high volume sampler (see Table 5). No distinction made between sulfates and sulfuric acid.
Methylthymol blue method	Samples collected as in the turbidimetric method above and extract reacted with barium chloride, but barium remaining in solution then reacts with methylthymol blue; sulfate determined colorimetrically by measurement of uncomplexed methylthymol blue (US Environmental Protection Agency, 1974b).	This modification allows the procedure to be automated, comments as in the turbidimetric method apply.

The most recent trends are towards the application of more sensitive techniques, such as X-ray fluorescence (Dzubay & Stevens, 1973), or the thermal conversion of sulfates, measuring the resulting sulfur dioxide by flame photometry (Husar et al., 1975), or by the pararosaniline method (Maddalone et al., 1975).

Approaches to the difficult problem of determining sulfuric acid have been made by back-titrating a sodium tetraborate extract of suspended particulates collected on a small filter paper (Commins, 1963), and by observing the acidic properties of individual particles collected on indicator-treated slides in a cascade impactor (Waller, 1963). A procedure for the separate determination of sulfuric acid and ammonium sulfate by nephelometry of a humidified sample of air has also been described (Charlson et al., 1973) and work is in progress on the prevention of the reaction of sulfuric acid on filter papers (Thomas et al., 1976). However, at present, there is not enough field experience with methods for sulfuric acid to warrant their general use in connexion with epidemiological studies.

2.2.3 Suspended particulate matter

In general, it is not practicable to discriminate on the basis of either particle size or chemical composition when assessing particulate matter for routine monitoring purposes. The characteristics of the sample are determined by the types of sources in the vicinity, the weather conditions, and the sampling procedure adopted. The difficulties that result and the limitations of measurements have been discussed by Ellison (1965) and are illustrated in the discussion of the merits and shortcomings of the various methods described below and in Table 5.

When considering measurements of suspended particulate matter, it is essential to specify the method used and to recognize that, even then, results obtained in one set of circumstances will not necessarily be applicable to others. The main difficulty has arisen in attempts to apply findings based on smoke measurements that relate only to the dark-coloured material characteristic of the incomplete combustion of coal or other hydrocarbon fuels, to situations involving total suspended particulates assessed more directly in terms of weight. Because the former have been used in much of the early epidemiological work and the latter are now used for monitoring purposes in many countries, some kind of conversion from one type of measurement to the other would be desirable, but, for the reasons already stated, there can be no generally applicable conversion factor. Comparative evaluation of the two methods has been undertaken at a number of sites (Ball & Hume, 1977; Commins & Waller, 1967; Lee at al., 1972), but the results have only served to emphasize that they measure different qualities of the particulate matter and that they should not be compared with one another.

Table 5. Methods of analysis for suspended particulate matter

Method	Principle	Comment
Smoke measurement: Organization for Economic Cooperation and Development filter soiling method	Air is drawn through a white filter paper, usually over periods of 24 h, and the darkness of the stain obtained measured by reflectometer; values converted to equivalent international smoke units, expressed conventionally, in $\mu g/m^3$; simple apparatus, suitable for continuous operation.	Widely used in Europe and recommended by the Organization for Economic Cooperation and Development (1965); low intake velocity ensures sample restricted to respirable size range; often combined with sulfur dioxide measurement by acidimetric method (see Table 2-3); results influenced primarily by black material do not necessarily represent true weights; only a limited range of chemical analyses possible on these small samples.
Smoke measurement: American Society for Testing and Materials filter soiling method	Similar to the Organization for Economic Cooperation and Development filter soiling method, but samples collected on a filter paper tape moved on automatically to provide a series of stains over intervals of 2-6 h (American Society for Testing and Materials, 1964); results usually assessed by transmittance, and expressed in coefficient of haze (COH) units (Hemeon et al., 1953; reflectance has sometimes been used, expressing results in reflectance units of dirt shade (RUDS) (Gruber & Alpaugh, 1954).	Flow rate a little greater than in the Organization for Economic Cooperation and Development filter soiling method but sample still effectively within respirable size range used in USA; interrelationships between Coh units and RUDS investigated by Saucier & Santone (1972); suitable for continuous operation.
Determination of total suspended particulates, gravimetric high volume	Air drawn through a glass fibre filter sheet, usually with a turbine blower, and the amount of material collected determined by weighing under controlled temperature and humidity conditions; the most widely used instrument is the high volume sampler (US Department of Health, Education and Welfare, 1962), but instruments based on rotary pumps with membrane rather than glass fibre filters have been used (Verein Deutscher Ingenieure, 1974).	Widely used in USA. Liable to collect particles well beyond the respiratory size range and this may bias results, particularly in dry, dusty locations; not very suitable for continuous operation, samples commonly collected over 24-h periods every sixth day; samples large enough for a wide range of chemical analyses.
Indirect determination of mass concentration: β ray sampler	Series of samples collected on filter paper strip over selected periods (usually 30 min), and mass of material determined by attenuation of β radiation from a built-in source (Husar, 1974).	Instrument relatively expensive; used for monitoring purposes in Federal Republic of Germany, but not to any large extent elsewhere; valuable for studying short-term variations in total suspended particulates.
Light scattering	Direct determination of suspended particulate matter as aerosols by light scattering, either counting and sizing individual particles (Liu et al., 1974) or integrating light scattered from given volume of air (Horvath & Charlson, 1969).	Used to some extent in Japan for monitoring suspended particulate matter, but calibration required and results not necessarily comparable with those from direct weighings; otherwise main application in industrial environments, some instruments allow particles to be counted and classified within a large number of size ranges.
Size selective sampling: modified cascade impactor	Particles separated into several roughly size-graded fractions by impaction, the amount of material in each being determined by direct weighing (Carson & Paulus, 1974).	Allows concentrations to be assessed within specified size ranges; some series of results available from USA but not yet widely adopted; applicable also to the sampling of dusts in industrial environments.
Electrostatic precipitators	Particles charged by passing through metal tube with large potential gradient between wall and needle along centre; deposited on wall and determined by direct weighing (Lauterbach et al., 1954).	Not suitable for outdoor measurements, but useful in occupational environments; advantage over direct weighing of filters is that the collector is unaffected by changes in humidity.
Personal samplers	Air drawn through small glass-fibre filters using battery operated pump, so that instrument can be worn by individuals (Sherwood & Greenhalgh, 1960); particulates assessed by weighing, or analysed for specific constituents.	Applicable primarily to industrial environments to assess exposures in series of working shifts; elutriator can be added to exclude large particles.

From their study in central London, Commins & Waller (1967) showed that additional material was collected by the high volume sampler that had little effect on smoke measurements and that for their particular series, the total suspended particulate results were approximately 100 $\mu g/m^3$ higher than the corresponding smoke figures. Other authors have calculated regression equations for their series and, although there are variations in these relationships with time and place, the general picture is of a large proportional difference between total suspended particulate and smoke figures at low values, but relatively little difference at high values (of the order of 500 μg of smoke/m^3 or more).

Thus, it is recommended that "smoke" and "total suspended particulate" measured by the various methods described should be regarded as separate entities; this principle has been adopted in later sections relating to the effects on health.

In occupational environments, suspended particulate matter from combustion sources may be of some concern, but more commonly it is the dusts and aerosols associated with particular occupations or processes that are of interest. In such cases, the composition of the material may be relatively uniform and well established, and specific methods of assessment can be devised. There has, for example, been a great deal of research and development on methods for determining dust concentrations in coal mines (Jacobsen, 1972). With industrial dusts, the particle size distribution must always be considered carefully, for it is liable to extend beyond the respirable range, and elutriators or cyclones may be needed in conjunction with gravimetric samplers. A valuable discussion of methods for collecting size-graded samples has been included in a recent review (International Atomic Energy Agency, 1978).

2.2.4 Dustfall (deposited matter)

In some of the older epidemiological studies, measurements of dustfall were quoted as an index of particulate pollution. This is inappropriate as the results are influenced primarily by large particles (diameters from about 10 μm upwards: see section 2.1.2) that do not penetrate the respiratory system and, generally, are not relevant to health problems, apart from possible annoyance reactions. For reference purposes, however, a brief description of one of the more commonly used instruments is included (Table 6).

Table 6. Method of analysis for dust fall

Method	Principle	Comment
Deposit gauge	A receiver containing a nonfreezing solution is left in the open and the quantity of material collected (usually over 1-month periods) is determined by weighing, water-soluble and insoluble components being considered separately (British Standards Institution, 1969b)	Results expressed in terms of deposit per unit area and time, not convertible in any way to concentrations of suspended matter in the air; strongly influenced by sources nearby, hence results only relevant to immediate vicinity

3. SOURCES OF SULFUR OXIDES AND PARTICULATE MATTER

3.1 Natural Occurrence

Compounds of sulfur are found in small quantities in ambient air, even in remote areas far from sources of pollution. In the gas phase, they are present as hydrogen sulfide or sulfur dioxide, and in particulate form they may be present as sulfate. Sulfur dioxide and hydrogen sulfide are emitted by volcanoes and the latter is also produced by anaerobic bacteria in soil, marshes, and tidal flats (Grey & Jensen, 1972). Some of the particulate sulfate may also be emitted directly by volcanoes or sea spray, but most of it is the end-product of the oxidation of hydrogen sulfide or sulfur dioxide.

In general, suspended particulate matter can result from volcanic activity, from dust storms, or from strong winds blowing over dry soil and may include pollen from trees and other plants. Forest fires also produce large amounts of particulate matter.

Some of these natural contributions to the particulate matter in the air consist of particles too large to remain in suspension for long periods, and their composition and properties may be quite different from those of the emissions from man's activities.

3.2 Man-made sources

Most emissions of sulfur into the air are in the form of sulfur dioxide resulting from the combustion of fossil fuel for heating and energy production. Various industrial activities such as petroleum processing, smelter operations, wood-pulping, etc., also produce significant emissions of sulfur dioxide and other sulfur compounds.

It has been estimated (Robinson & Robbins, 1968) that on a worldwide scale about 146×10^6 tonnes of sulfur dioxide are emitted annually, 70% of which result from coal burning, 16% from the combustion of petroleum products, and the remainder from petroleum refining and nonferrous smelting. These estimates are based mainly on 1965 world figures for coal production, petroleum refining, and smelter operations, each combined with an estimate of a sulfur dioxide "emission factor" per unit of production. A similar basis was used for the Committee on the Challenges of Modern Society (1971) assessment of emissions in the northern and southern hemispheres, reproduced in Table 7.

On a global scale, the emissions of sulfur compounds into the atmosphere by man-made activities are about equal to those from natural sources. On the other hand, the emissions from man's activities are the main contributors to pollution in large cities and their surrounding areas. Assuming that world energy demand increases at its historic rate, the total emissions of sulfur

Table 7. Hemispheric sulfur dioxide emmissions due to man's activities (10^6 tonnes per year)[a]

Source	Total	Northern Hemisphere	Southern Hemisphere
Coal	102	98 (96%)	4 (4%)
Petroleum, combustion and refining	28.5	27.1 (95%)	1.4 (5%)
Smelting, copper	12.9	8.6 (67%)	4.3 (33%)
lead	1.5	1.2 (80%)	0.3 (20%)
zinc	1.3	1.2 (90%)	0.1 (10%)
Total	146	136 (93%)	10 (7%)

[a] From: Committee on the Challenges of Modern Society (1971).

dioxide will increase unless appropriate control measures are applied, or there is a shift from the use of fossil fuels to the use of nonpolluting energy sources. However, with the stabilization of the population in some countries, including the United Kingdom and USA, and increasing concern about the use of limited fuel reserves, there are prospects that the rate of increase in emissions may be reduced in some parts of the world.

Combustion and industrial processes are also prime sources of particulate emissions. As with sulfur dioxide, the burning of fuel (especially coal) for heating and for the generation of power has been one of the major contributors to the suspended particulate matter in urban air. Vehicular traffic also generates dust from the road and from the wear of tyres as well as particulate lead compounds from the exhausts of petrol-engined vehicles, and black smoke from those of diesel vehicles. The incineration of domestic and industrial refuse may disperse particulate matter and other pollutants into the air unless carefully controlled. Table 8 shows estimates of the global emission of all particulate matter (Robinson & Robbins, 1968).

Table 8. Global emission of all particulate matter (10^6 tonnes per year) [a]

Man-made		
Particles		92
Gas-particle conversion:	sulfur dioxide	147
	oxides of nitrogen	30
Photochemical compounds from hydrocarbons		27
		296
Natural		
Soil dust		200
Gas-particle conversion:	hydrogen-sulfide	204
	oxides of nitrogen	432
	ammonia	269
Photochemical compounds from terpenes, etc		200
Volcanic		4
Forest fires		3
Sea salt		1000
		2312

[a] From: Robinson & Robbins (1968).

3.3 Characteristics of Sources

In urban areas, most of the sulfur dioxide and suspended particulate matter in the air come from the combustion of fuels, but many factors, including the type of fuel, the combustion efficiency, and the flue velocity, influence the quantity and quality of emissions. The incomplete combustion of soft coal in domestic fires, for example, produces much smoke, consisting of finely divided particles of carbon and tarry material, whereas the efficient burning of pulverised coal in a power station leads to little or no smoke, but the production of coarser ash particles, which must be removed at source to avoid their being carried up the flues at a high velocity and dispersed into the air. The relationship between types of sources and emissions is summarized in Table 9.

Table 9. Pollutants from combustion sources

Type of source	Fuel	Sulfur dioxide	Particulate matter	
			Smoke	Ash etc.
Domestic heating or cooking	Wood, peat etc.	–	+	+
	Soft coal	++	++	+
	Hard coal, coke	++	–	+
	Oil (light distillates)	+	–	–
	Gas	–	–	–
Industrial heating and power generation	Coal, coke	++	–	++
	Oil (heavy residuals)	++	–	–
Motor vehicles	Petrol	–	–	+
	Diesel	+	+	–

Notes: The term smoke is used for incomplete combustion products (notably carbon and tar), and ash for inorganic components from complete combustion (including lead compounds in the case of petrol). The signs give only a rough indication of emissions, in the absence of direct control at source:
– = little or none, + = moderate quantities, ++ = large quantities

In cold and temperate parts of the world, the burning of coal for domestic heating purposes has been a major contributor to both the sulfur dioxide and suspended particulate contents of urban air. This is particularly true of the situation in the United Kingdom prior to the implementation of the Clean Air Act (Committee on Air Pollution, 1954). Such sources are liable to have a disproportionate effect on concentrations in the immediate vicinity, because of the low levels of the chimneys and the low emission velocity. Even in warmer climates, domestic sources may be of importance, particularly if coal is used for cooking purposes.

In densely populated areas where domestic sources dominate, the many chimneys can be considered for some purposes as a diffuse area source, and, within such an area, concentrations of pollutants in air remain relatively stable over short distances and short periods of time. In contrast, large industrial sources should be treated as point sources, and, at any given location

around them, the concentration of air pollution is liable to vary greatly, even from minute to minute.

The emission into the air of sulfur dioxide and particulate matter from motor vehicles is relatively small in comparison with those from domestic and industrial chimneys but it is close to the ground and within the breathing zone. In these circumstances, concentrations vary greatly over short distances as well as over short time intervals, depending on the proximity of the traffic. At points very close to mixed traffic, smoke from diesel engines may make a substantial contribution to the concentration of suspended particulate matter in air (Waller et al., 1965).

Source strength may vary with time of day, day of week, and season of the year. Accompanying meteorological conditions are also important in determining the ultimate air concentrations of pollutants arising from sources. Where heating is required during the winter season, emissions of sulfur dioxide and particulate matter are usually much higher than they are in the summer. In a number of cities, however, where a considerable amount of fuel is used for running cooling systems, emissions of these pollutants during the summer time are not always lower than those in winter. Some industrial sources of pollution may emit little at weekends, and emissions for most sources are at a minimum during the night.

Although the control of emissions is outside the scope of the present discussion, the general point can be made that while the control of particulate emissions is a practicable proposition in many circumstances, the control of sulfur dioxide at source is relatively difficult and costly, and the more effective means of reducing emissions is to change to fuels with a lower sulfur content.

4. DISPERSION AND ENVIRONMENTAL TRANSFORMATIONS

Sulfur compounds dispersed into the air eventually return to the land or oceans either unchanged, or converted into sulfates. The sulfur cycle so set up is shown diagrammatically in Fig. 4 (Kellogg et al., 1972). Particulate matter also returns, its residence time in the air varying widely according to its physical and chemical characteristics. As far as direct effects on health are concerned, it is the local concentration of pollutants in the air at a given time that is important, as discussed in section 5, but an outline of dispersion and transformation phenomena is given here.

4.1 Dispersion

The maintenance of a tolerable environment in modern towns depends very much on the ability of wind and turbulence to disperse the pollutants rapidly as they are emitted. When these processes fail, the results can be disastrous, as they were in London in 1952 (Ministry of Health, United

Kingdom, 1954). There are some localities where natural ventilation is so poor that the emission of pollutants must, at all times, be carefully controlled. This is especially true of the Los Angeles area, where emissions of sulfur dioxide and particulate matter have been successfully curtailed, leaving, however, the major problems associated with the emission of oxides of nitrogen, hydrocarbons, and carbon monoxide from motor vehicles (Goldsmith, 1969).

Factors affecting the dispersion of sulfur dioxide and particulate matter from combustion sources, include:

(*a*) *Temperature and efflux velocity of the gases*. Emissions from small sources, such as domestic fires or incinerators have relatively little buoyancy, since the temperature at the point of emission is not much greater than that of the surrounding air. Such sources are liable therefore to have their greatest impact in the immediate vicinity (Williams, 1960). Emissions from large-scale industrial installations, on the other hand, may be at higher temperatures, or may be assisted by forced-draught to rise more rapidly. Thus, any major impact in the immediate vicinity may be avoided but weaker effects may be produced over a wider area (Bosanquet, 1957).

(*b*) *Stack height*. Dilution and dispersion over a wide area is also aided by the use of tall stacks. Much is known of the relationship between source

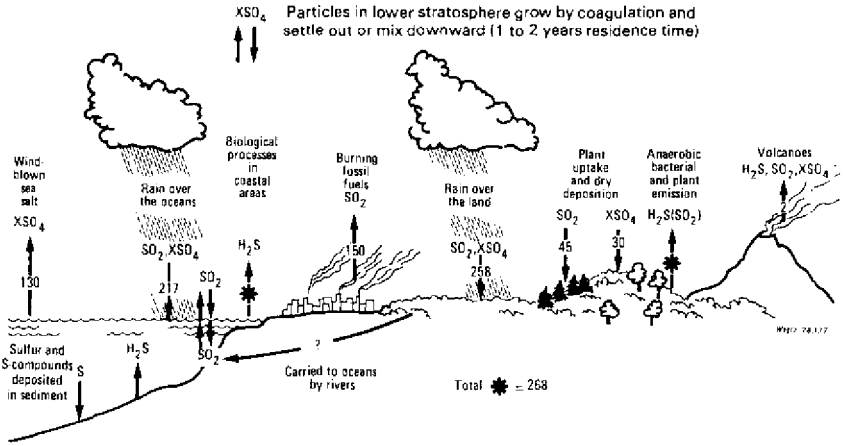

Fig. 4. Sources and sinks of atmospheric sulfur compounds. Units are 10^6 tonnes calculated as sulfate per year (From: Kellogg et al., 1972).

strengths, stack heights, and ground-level concentrations of pollutants, through the application of mathematical modelling techniques, coupled with observations around selected sources (Briggs, 1965, Pasquill, 1971, Turner, 1968). It is also possible to devise models to predict concentrations of sulfur dioxide in urban areas on the basis of emissions from multiple sources

(Fortak, 1970). Conversely, techniques have also been developed for estimating the pollution inventory of an area from measurements of sulfur dioxide concentration, fitted to a dispersion model (East, 1972). The height of emission of sulfur dioxide and particulate matter from domestic sources is primarily a function of the height of the building itself. Thus the effect on ground level concentrations in the vicinity is liable to be greater in areas with closely-packed, single or two-storey houses than in those with high-rise apartments. Tall stacks are widely used for electricity-generating stations and other major industrial sources, but the pollutants may then be carried great distances, often over national boundaries, to be deposited eventually far from their source (Royal Ministry of Foreign Affairs, Sweden, 1971; Zeeduk & Velds, 1973).

(*c*) *Topography and the proximity of other buildings*. The presence of hills or tall buildings, and many other features of the landscape, have important effects on the dispersion of plumes from individual stacks, or of the pollution from an area source as a whole. Many industrial cities have developed in river valleys, initially to take advantage of water transport, but, in general, the dispersion of pollutants in such a situation is poorer than it would be from a more exposed location.

(*d*) *Meteorology*. Meteorological factors are of fundamental importance in determining the whole spatial and temporal distribution of pollution, and the subject has been well reviewed in a recent publication (Munn, 1976). Apart from the general influence of the local climate, the great variability of the weather in any one locality is liable to lead to considerable changes in the concentrations of sulfur dioxide. In particular, temperature inversions can trap these pollutants to produce concentrations up to several hundred times the usual values (Waller & Commins, 1966).

4.2 Transformation and Degradation

In recent years, there has been a rapid escalation of interest in the ultimate fate of sulfur dioxide and particulate matter emitted into the air. This is concerned partly with the nature of reaction products and their possible effects on health, and also with the ecological effects of these products when deposited (Brosset, 1973) and their possible role, as aerosols, in modifying the climate on a global scale (Hobbs et al., 1974).

Some of the sulfur dioxide emitted into the air is removed unchanged by various surfaces, including soil (Abeles et al., 1971), water (Liss, 1971; Spedding, 1972), grass (Garland et al., 1973) and vegetation in general (Hill, 1971). It has been estimated that, in the United Kingdom, about 25% of the sulfur dioxide is removed by these direct ("dry" deposition) processes (Garland et al., 1974). The remainder is transformed into sulfuric acid or

sulfates by a variety of processes, in the presence of moisture, and is then mainly washed out in rain. Although this self-cleansing process limits the build-up of sulfur compounds in the air, so minimizing the effects on health, the "acid rain" produced is considered to be a serious general environmental problem in some areas (Likens & Bormann, 1974).

A schematic representation of a natural sulfur cycle is shown in Fig. 5 (Kellogg et al., 1972). Additons to this cycle due to man's activity are possible at each stage, although 95% of such contributions are added as sulfur dioxide. Also represented here are the possible reactions with sunlight. There have been many laboratory investigations of this process: the reaction is slow (Allen et al., 1972; Cox & Penkett, 1970), but it is enhanced in the presence of hydrocarbons and other pollutants associated with motor vehicle emissions (Cox & Penkett, 1971; Wilson & Levy, 1970). In general, however, other processes are of even greater importance in the transformation and removal of sulfur dioxide, including reactions in water droplets with ammonia (McKay, 1971), and catalytic oxidation in the presence of manganese or iron (Barrie & Georgii, 1976; Chun & Quon, 1973). These various reactions involving sulfur dioxide, particulate matter, and other pollutants have been discussed in a

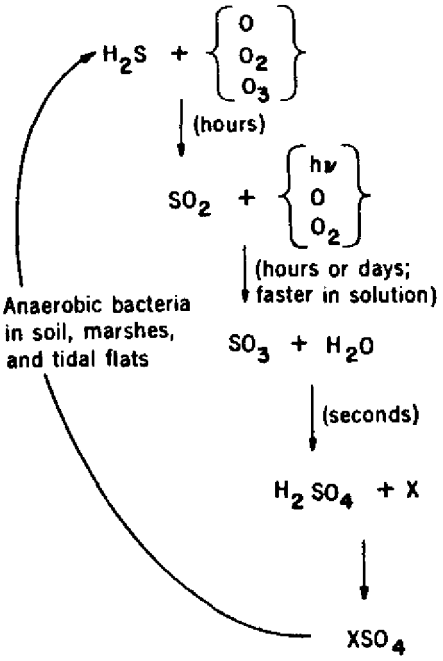

Fig. 5. Schematic representation of the chemical process involving environmental sulfur, with indications of the mean lifetime of each compound in the lower atmosphere (From: Kellogg et al., 1972). Copyright 1972 by the American Association for the Advancement of Science.

number of reviews (Bufalini, 1971; Calvert, 1973). There may be limitations to the catalytic processes because of the restricted availability of reactive metallic oxide, catalytic particles, and neutralizing compounds in the air. Some of the photochemical reactions are severely rate-limited, but in others, sulfur dioxide can be oxidized at an appreciable rate and it has been estimated that conversion rates as high as 18% per hour might be possible (Rall, 1974). The end-products are similar in all these reactions, i.e., the formation of aerosols, initially in the submicron size-range, consisting of a mixture of sulfates and sulfuric acid. There is no uniform relationship between the proportions of sulfur dioxide, sulfates, or sulfuric acid in the total sulfur pollution. Emissions are primarily in the form of sulfur dioxide; thus, in cities close to sources, the major proportion is in this form, but it has been reported that, in the USA, the proportion present as sulfate is higher in western than in eastern urban areas (Altshuller, 1973). At nonurban sites, concentrations of sulfates may be similar to those of sulfur dioxide.

The overall conversion of sulfur dioxide to sulfate is an extremely complex process with many interrelated variables that are poorly characterized. These include the absorption rate of sulfur dioxide, the sizes of the particles or droplets involved, their chemical composition, the rate of diffusion of reactants within the aerosol, and the relative humidity. The last of these variables is a major factor, as the catalytic reactions occur with water droplets containing absorbed sulfur dioxide and other pollutants. Furthermore, as the pH decreases, the rate of oxidation of sulfur dioxide also decreases (Junge & Ryan, 1958). Thus, the formation of sulfuric acid tends to be self-limiting unless the fall in pH is offset by additional water vapour. On the other hand, the presence of alkaline compounds, such as ammonia, in the droplet can enhance the reaction rate due to its buffering capacity. Extrapolated levels for the rate of oxidation of sulfur dioxide by catalytic processes in urban air range upwards from 2% per hour (Rall, 1974). Overall, the half-life of sulfur dioxide in ambient air is estimated to be three to five hours.

The physical and chemical forms of suspended particulate matter in general may be changed in the air. Some components, such as hydrocarbons, absorbed initially onto particulate matter, may evaporate or be oxidized. Even some of the complex hydrocarbons in the tarry matter from coal burning may be volatile enough to be lost gradually, and there is evidence that they can be lost from filters during sampling (Commins & Lawther, 1958). The sizes of the particles may vary according to the relative humidity, particularly if sulfuric acid, sulfates, or other salts are present, and this can lead to precipitation even before the onset of rain (Waller, 1963). The question of overwhelming importance is the role of particulate matter in the conversion of sulfur dioxide to sulfuric acid and sulfates. Traces of metallic compounds, some of which serve as catalysts in these reactions, are present in particulate

matter from the combustion of coal, and also in the relatively small amount of particulate matter that may come from the combustion of oil. It has long been considered that the acute effects on health seen in episodes of high pollution are crucially dependent on the mixture of sulfur dioxide and particulate matter present, together with the relative humidity: the worst effects have been seen with each of these factors in a high range (Ministry of Health, United Kingdom, 1954).

5 ENVIRONMENTAL CONCENTRATIONS AND EXPOSURES

Sulfur dioxide and suspended particulate matter are the most widely monitored air pollutants. National sampling networks exist in many of the industrialized countries of the world, and summaries of the observations are commonly published in annual reports. Results from selected sampling sites are also collated by a number of international organizations (Commission of the European Communities, 1976; Pan American Health Organization, 1976; World Health Organization, 1976b).

5.1 Concentrations in Outdoor Air

Most sampling networks for sulfur dioxide, smoke, and suspended particulate matter have been set up for control purposes, to examine the distribution of these pollutants in various areas and to follow the long-term trends. Such measurements are normally made on outdoor air. Where adequate networks exist, there is obviously an advantage in trying to use them to assess exposure, but this may be far from ideal. The limitations of the data obtained from the usual monitoring sites may, to some extent, account for inconsistencies in results in studies reviewed in section 8. Requirements for monitoring networks have been discussed further in a recent report (World Health Organization, 1977).

Concentrations of sulfur dioxide and suspended particulate matter vary greatly from one area to another depending on the nature and intensity of local sources, and on other factors such as topography, general weather conditions, and liability to temperature inversions. Even within a single city there may be large differences in concentrations. Where sufficient monitoring stations exist, it may be possible to construct isopleths, showing "contours" of equal concentration. An example, for the city of Antwerp, is shown in Fig. 6 (Derouane et al., 1972). From this, it is clear that the distribution of sulfur dioxide is not necessarily the same as that of smoke. There is a general tendency for the concentrations of these pollutants to be highest in the largest cities of the world, and within them for the highest concentrations to be in the central areas. The implementation of control measures has, however,

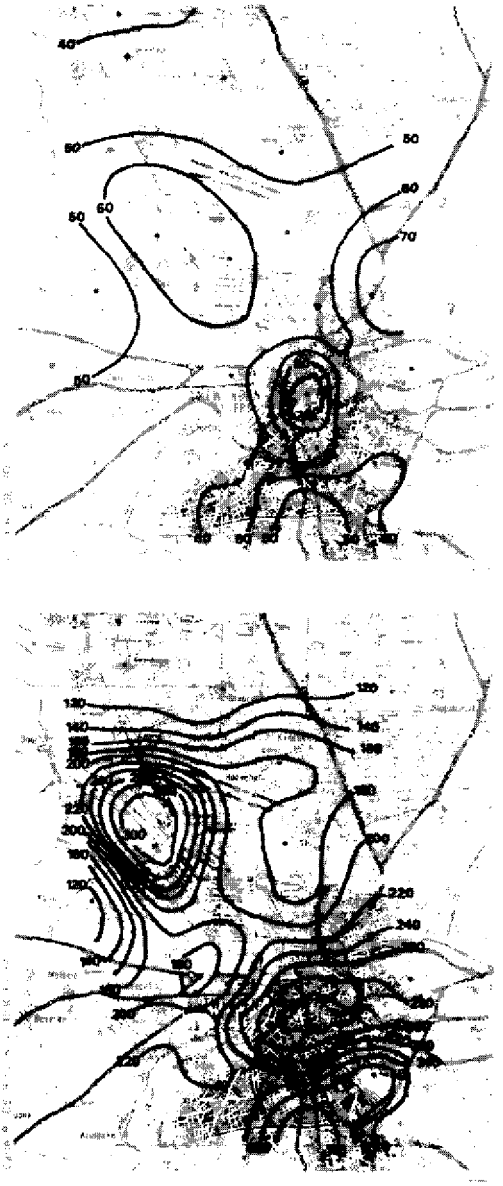

Fig. 6. Mean concentrations ($\mu g/m^3$) of smoke (upper map) and sulfur dioxide (lower map) plotted as contours, city of Antwerp, winter (1.10.69–31.3.70) (From: Derouane et al., 1972).

changed the situation in recent years, for, in some instances, these have been applied most vigorously in the central areas of large cities (Masters, 1974).

Table 10. Concentrations of sulfur dioxide, smoke, and suspended particulate matter (1974)[a]

Site	Concentration (μg/m3)	
	annual arithmetic mean	maximum daily mean
Sulfur dioxide		
Brussels	107	347
Frankfurt	119	455
London	150	503
Madrid	161	763
Prague	126	482
Rome	108	600
Zagreb	173	893
Smoke, by reflectance		
Brussels	37	–
London	26	149
Madrid	190	908
Rome	60	160
Suspended particulate by high volume sampler		
Calcutta	519	1090
St Louis	87	189
Vancouver	64	134
Zagreb	167	806

[a] From: World Health Organization (1976b). Sites selected for inclusion here are all classified as city centre commercial sites. The selection is also limited to sites using 24-h averaging periods. Further information is available in the WHO report of frequency distributions, standard deviations, and monthly and annual geometric means.

Examples of concentrations of sulfur dioxide and smoke or suspended particulate matter, drawn from the WHO air quality monitoring programme (World Health Organization, 1976b) are shown in Table 10. For present purposes, results included in this table are limited to those from one type of site (city centre commercial sites), where the sampling methods and averaging periods are also comparable with one another. Even so, much caution must be exercised in drawing comparisons between cities, for the sites can only be representative of their immediate surroundings.

The annual mean concentrations of sulfur dioxide are fairly uniform at the particular sites quoted in Table 10, ranging from about 100 to 200 $\mu g/m^3$ (0.035-0.070 ppm). For particulate matter, however, the variation between cities appears to be much greater and it seems likely that some of the results are unduly influenced by sources close to the samplers, or by high background levels of dust from noncombustion sources.

There are few reports about ambient levels of sulfates. A study from the USA (Altshuller, 1973) reported annual, arithmetic mean concentrations at urban sites in the range of 2.4 to 48.7 $\mu g/m^3$, with an average ratio of sulfur dioxide to sulfate of 4.7. The relationship between these two pollutants was not, however, entirely consistent and the ratio tended to be higher at western sites than at eastern sites. In the east, there was a general background level of sulfate of about 5 $\mu g/m^3$, even at nonurban sites, and this was attributed to the long distance transport of sulfur dioxide, with conversion to sulfate

during transport. There also appeared to be a "saturation" level of sulfate at about 17 $\mu g/m^3$ at eastern urban sites, within the sulfur dioxide range of 100-200 $\mu g/m^3$ (0.035-0.070 ppm).

There is even less published information concerning concentrations in air of sulfuric acid, and such observations must always be related to the method of measurement. One series of measurements of net particulate acid, as determined by titration of samples collected on filter papers, has indicated a mean concentration in London of approximately 4 $\mu g/m^3$, representing a few percent of the corresponding concentration of sulfur dioxide (Commins & Waller, unpublished data). However, the concentration of this pollutant is liable to increase rapidly during temperature inversions, particularly if the relative humidity is high (Commins, 1967).

For each of the pollutants considered, there are generally large variations in concentration with time at any one place. The extent to which this can be followed depends on the time resolution of the sampling instruments. Usually, integrated samples are collected over 24-h periods to yield daily mean values, and from these monthly, seasonal, and annual means are calculated. Shorter sampling periods may however be used, and where continuous automatic instruments are used, virtually instantaneous values can be obtained. Relationships between values averaged over different periods have been extensively studied in the USA (Larsen, 1971). An indication of the day-to-day variation in smoke and sulfur dioxide concentrations in a large city (London) is given in Fig. 7.

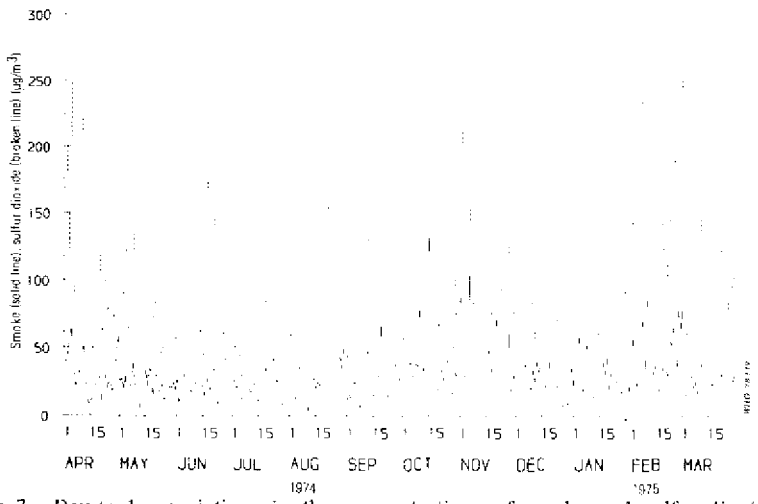

Fig. 7. Day-to-day variations in the concentrations of smoke and sulfur dioxide in London (means of 7 sites), 1974-75 (From: Medical Research Council Air Pollution Unit, now, Clinical Section of Medical Research Council Toxicology Unit, London, UK, unpublished data).

Although annual means, coupled with daily maxima, give a general impression of pollution levels in any given locality, long series of results are often summarized as frequency distributions. These have been shown to be log-normal for a wide range of averaging times, pollutants, and localities (Pollack, 1975). This suggests that the geometric mean, which, in such a case, is equivalent to the median, is perhaps the most appropriate central value to use. Historically, however, the arithmetic mean has been more widely used. For the usual log-normal distribution, the geometric mean is a little lower than the arithmetic mean. Percentiles of the frequency distribution are tabulated in some monitoring networks (US Environmental Protection Agency, 1974a), and the complete distributions can conveniently be plotted on log-probability paper, as in the example in Fig. 8 drawn from data for a recent 5-year period in London (Commins & Waller, unpublished data).

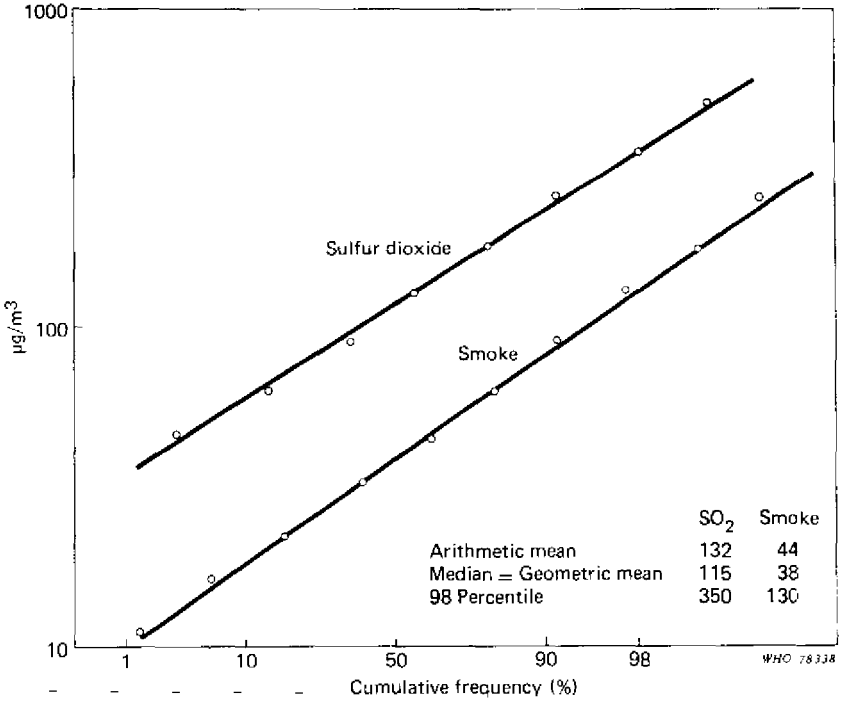

Fig. 8. Cumulative frequency distributions of daily smoke and sulfur dioxide observations in Inner London (means of 7 sites), 1969-74 (log-probability scale) (From: Commins & Waller, unpublished data).

Relationships between peak and mean values for sulfur dioxide have also been considered on an empirical basis. For a number of cities in Europe, the

highest daily mean concentrations during the year have been found to be of the order of four times the annual means (Commission of the European Communities, 1976). Transient peaks in continuous records have been examined in the USA in relation to averaging times: the ratio of peak to mean values has been found to be 2.3 for hourly averaging periods, increasing for successively longer periods (Montgomery & Coleman, 1975). Some highly sophisticated networks exist for the measurement of sulfur dioxide on a continuous basis at many points. The collection and interpretation of such data then presents a formidable task, and in some of these networks on-line computers are used for data acquisition (Lauer & Benson, 1975).

The examination of trends in the concentrations of sulfur dioxide and particulate matter is important when the effects of long-term exposures are investigated. In urban areas of most developed countries, there has been a tendency for levels to decline in recent years as a result of control efforts, although elsewhere, and particularly where concentrations of these pollutants had previously been low, increases have occurred as emissions from industrial

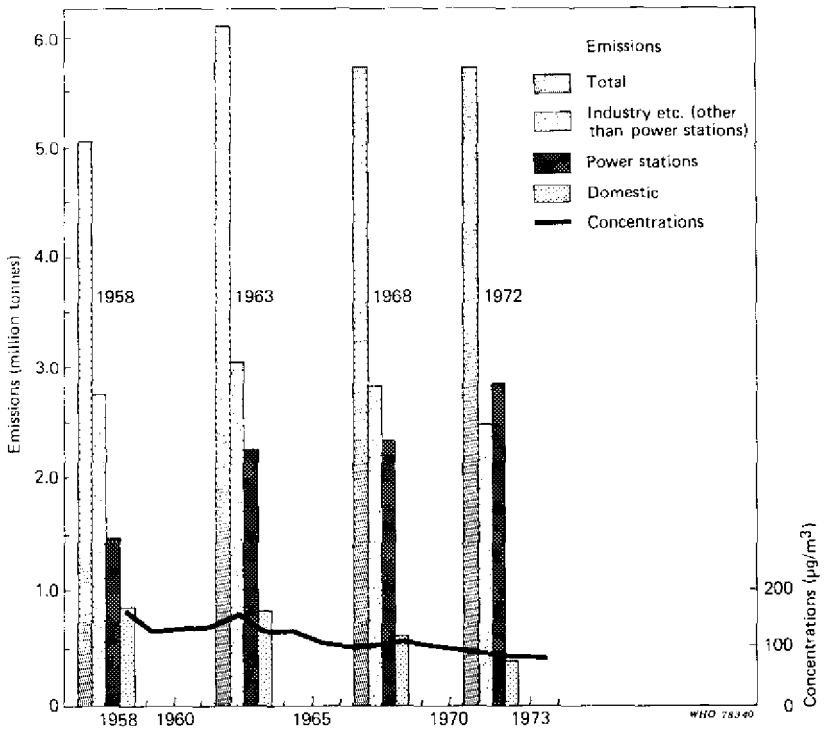

Fig. 9. Trends in emissions and concentrations of sulfur dioxide in the United Kingdom 1958-73 (From: Weatherley et al., 1976). Crown copyright, reproduced by permission of the Director, Warren Spring Laboratory.

and other sources have increased. Since variations in weather patterns from year-to-year can affect even the annual mean concentrations, long series are required to examine trends adequately. The declining trend in sulfur dioxide concentrations seen in a number of large cities in Europe during the 1960s (Commission of the European Communities, 1976) may, to a large extent, reflect declining emissions or improved dispersion from chimneys, but some authors have considered that changing weather conditions have been a contributory factor (Van Dop & Kruizinga, 1976). In the United Kingdom, there has been an overall decline in sulfur dioxide concentrations without a corresponding decline in total emissions (Fig. 9). This is attributable to the gradual elimination of sources, such as domestic fires, that had a substantial effect on local concentrations, and their replacement by a smaller number of large sources dispersing the sulfur dioxide more widely. In the case of smoke, concentrations in the United Kingdom have declined in parallel with the emissions (Fig. 10). Domestic fires always had a dominant effect, and these have been subject to control in an increasing number of urban areas.

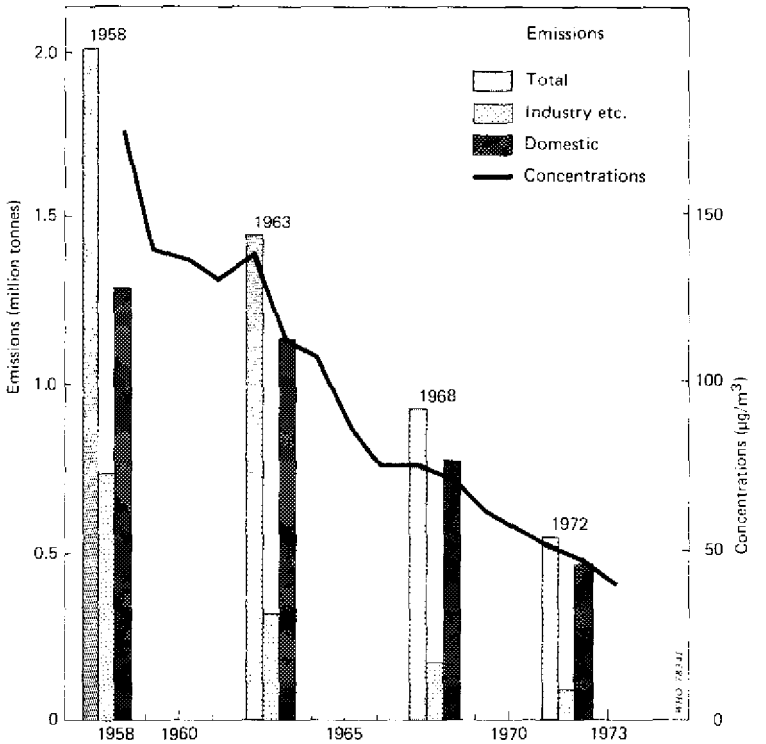

Fig. 10. Trends in emissions and concentrations of smoke in the United Kingdom, 1958-73 (From: Weatherley et al., 1976). Crown copyright, reproduced by permission of the Director, Warren Spring Laboratory.

5.2 Concentrations in Indoor Air

As yet, there is relatively little information available concerning the concentrations of sulfur dioxide and particulate matter in indoor environments (excluding those specifically related to occupational exposures). It is quite possible to make such measurements indoors by most of the methods mentioned in section 2, subject to additional care about interfering substances, and limitations of noise for equipment such as the high volume sampler. The results are, however, of limited value for general monitoring purposes, because of the additional variability introduced by the circumstances within each building. As far as human exposure is concerned, much time is spent indoors, particularly by the oldest and youngest members of the community, and information on indoor concentrations is required for epidemiological studies.

Whether there are substantial differences in indoor and outdoor concentrations of sulfur dioxide and particulate matter will depend on the degree of ventilation, the capacity of surfaces within to absorb or otherwise collect these pollutants, and the presence of sources either of the pollutants themselves, or of others that may interact with them.

In warm climates not subject to frequent rain or other adverse weather conditions, buildings may be left open enough to ensure that indoor concentrations of pollutants are virtually the same as those outdoors. Even so, there can be local problems associated with the use of fuels in equipment with poor flues or without flues. Extremely high concentrations of pollutants, including smoke, have been reported inside primitive dwellings in tropical regions, where cooking is carried out over open fires (Sofoluwe, 1968). The open coal fires that were so widely used in the United Kingdom prior to the Clean Air Act of 1956 had two possible, and opposing, effects on indoor concentrations. The very large ventilation rate that they induced helped to maintain indoor concentrations of smoke and sulfur dioxide close to those outdoors, but, in unfavourable wind conditions, downdraughts could force these pollutants from the fire itself into the room, producing concentrations far in excess of those outdoors. Examples of indoor concentrations of suspended particulate matter or (more rarely) of sulfur dioxide exceeding those out of doors have also been found in studies in the Netherlands (Biersteker et al., 1956) and in the USA (Yocom et al., 1971).

In general, however, in the absence of specific sources of sulfur dioxide or fine particulate matter indoors, concentrations are generally less than those outdoors. Sulfur dioxide as a gas, can diffuse readily onto walls and other surfaces. There is evidence that it reacts with ammonia from the indoor air on painted surfaces, particularly in the presence of moisture (Holbrow, 1958), but it is most effectively absorbed on clothing, curtains, carpets, and other

soft furnishings, so that in domestic surroundings where these abound concentrations of sulfur dioxide are only of the order of 20% of those outdoors (Weatherley, 1966), while in offices and other buildings containing less absorbing material, concentrations may be 40-50% of those outdoors (Andersen, 1972; Derouane, 1972). The presence of ammonia in occupied rooms is important in relation to measurements of sulfur dioxide. Concentrations of this "natural" pollutant may be much higher than outdoors, particularly where there are young babies or old people with incontinence problems. The ammonia will only react effectively with sulfur dioxide in the presence of moisture, but it will, in any case, interfere with the determination of the sulfur dioxide by acidimetric or conductometric methods.

Smoke, that is to say the finely divided black material from incomplete combustion, can penetrate fairly readily into buildings, and since the mobility of the particles is less than that of sulfur dioxide molecules, they are less rapidly removed onto surfaces. Concentrations of smoke indoors, assessed by soiling methods, have been found to be in the range of 50-90% of those outdoors (Derouane, 1972; Yocom et al., 1971), again assuming there is no specific source of this material inside. Cigarette smoke can make a very substantial contribution to the finely divided particulate matter indoors (Elliott & Rowe, 1976; Hoegg, 1972). It is liable to affect direct gravimetric concentrations, but it has relatively little effect on concentrations measured by blackness. The composition of cigarette smoke is quite different from that of the general urban particulate matter, and it has been stressed by De Graaf & Biersteker (1972) that there may be many differences in the type and composition of suspended particulate matter indoors and outdoors. This point is particularly important in relation to samples obtained with the high volume sampler. The larger particles (greater than 10 μm diameter) that are liable to be collected by this method would penetrate into buildings less readily than the fine particles, and, with reduced air movement inside, they may fall out fairly rapidly under gravity. This may account for the smaller proportion of total suspended particles (as compared with smoke) found indoors in some studies (Yocom et al., 1971). However, on the other hand, there is a risk that textile and other dusts dispersed in the home may be sampled and assessed as part of the general suspended particulate matter.

Sulfuric acid is unlikely to remain for any appreciable time in occupied rooms, as it is readily neutralized by ammonia. However, finely divided sulfate particles are likely to behave in the same way as smoke, with a modest reduction indoors compared with outdoors. Relative humidity is normally lower indoors than outdoors and this will help to keep sulfate particles in suspension, but where the humidity is especially high, as it may be in kitchens, particles containing sulfates or other salts will grow rapidly and be deposited.

Studies on indoor concentrations of sulfur dioxide and particulate matter are limited primarily by the need to consider the circumstances of each location individually; nevertheless, there is a growing body of literature on the subject that has been assembled and reviewed in recent reports from the USA (Benson et al., 1972; Henderson et al., 1973).

5.3 Concentrations in Work Places

Concentrations of sulfur dioxide, much higher than those commonly found in urban air, may be present in some industrial environments, arising from processes in which the gas is handled or evolved, as well as from combustion sources. Paper mills, sulfuric acid plants, steel works, nonferrous metal foundries, and oil refineries are among the places where such concentrations may be found. However, emissions are usually highly localized and intermittent, presenting major problems in assessing concentrations to which workers may be exposed. Results are not normally published, but in a number of countries there is a requirement to ensure that a specified limit is not exceeded. For example, in the USSR, the maximum permissible concentration is 10 mg/m^3 (3.8 ppm) (ILO/WHO Committee on Occupational Health, 1970) whereas in the USA (American Conference of Government Industrial Hygienists, 1977), this value, averaged over 8-h shifts, is 13 mg/m^3 (5 ppm). This figure is of the order of 100 times the average values in urban air and it is higher than the maximum values reported, even in episodes of high pollution (Waller & Commins, 1966). Mean values over 3 years of 1800-2100 μg/m^3 (0.6-0.7 ppm) have been reported close to blast furnaces in steelworks, with occasional 24-h mean values up to 17 000 μg/m^3 (5.95 ppm) (Lowe et al., 1970).

In steelworks, substantial quantities of suspended particulate matter may be present as well as sulfur dioxide and other pollutants. A 3-year mean concentration of about 1000 μg/m^3 (respirable dust, as measured with a Hexhlet sampler) has been reported in the study cited above (Lowe et al., 1970). Even so, the situation does not necessarily parallel that in urban atmospheres, for the particulate matter is liable to include dust which differs in composition and size distribution from that produced in the usual range of combustion processes.

Dusts encountered in industry must, in general, be considered separately from the suspended particulate matter in urban air. Some, such as the coal-dust in mines, may be present at high concentrations, and have substantial effects on health, but these are specific to that dust, and are outside the scope of the present discussion. However, some of the chemical compounds in dust from industrial activities are covered by other documents of the WHO environmental health criteria programme.

In some industries, such as wood-pulping and paper-making, sulfur dioxide may be evolved in the process, producing high concentrations locally without

an accompanying particulate matter problem. Concentrations in the range 6 to 100 mg/m^3 (2 to 36 ppm) have been reported at a plant in Norway (Skalpe, 1964) and similar concentrations were found in a study in the USA (Ferris et al., 1967) but these were gradually reduced over a 5-year period. High concentrations, averaging about 71 mg/m^3 (25 ppm), also existed at one time in charging rooms for refrigerators when sulfur dioxide was used as a refrigerant (Kehoe et al., 1932) and similar concentrations have been reported in certain areas of oil refineries (Anderson 1950).

There is a specific problem of sulfuric acid mist in the forming departments of works making lead-acid accumulators, where concentrations up to 16.6 mg/m^3 have been observed (Malcolm & Paul, 1961; Williams, 1970). This is very much greater than the concentrations ever found in urban air (Commins & Waller, 1978) and the physical form of the aerosol is different: mass median diameters of the droplets have been reported to be over 10 μm (Williams, 1970) whereas those found in urban air are of the order of 0.5 μm (Waller, 1963).

5.4 Assessment of Exposures

In the present context, the term exposure relates to the concentrations of sulfur dioxide or suspended particulate matter in the air breathed by individuals or populations, averaged over specified periods. Broadly speaking, two types of exposure are considered: short-term exposure, in which the relevant concentrations are averaged over periods of the order of a day, and long-term exposure, for which averages over periods of the order of a year are commonly used. These periods are to a certain extent arbitrary, imposed by the time-resolution of the pollution measurements and by the nature of the health indices examined, and there is no clear guidance on the most relevant averaging periods to use in relation either to short-or to long-term exposure.

Exposures are usually estimated from measurements of concentration at fixed sampling sites. The number of sampling sites required to give an adequate representation of the exposure of people living in a given area will depend on the topography, the distribution of sources, and other factors. In urban areas, there is usually a close correlation between values for neighbouring stations (Prinz, 1970). Care must be taken, however, to ensure that these stations are not used to represent environmental levels in areas much larger than their coverage. Furthermore, the instruments for measurement may be sited on the roof of a building for protection and convenience, and the levels measured may not necessarily represent those in the ordinary breathing zone.

The usual practice in epidemiological studies is to assume that measurements made on outdoor air in the areas where people live or work provide an index of exposure that allows comparison to be made between different groups. It

has been demonstrated, however, that estimated weekly exposures calculated as averages of concentrations measured indoors and at various outdoor sites and weighted according to the length of time likely to be spent in each location, may differ substantially from those indicated by measurements at just one site close to the place of residence or work (Fugaš, 1976). To validate this approach, further measurements using personal samplers would be required. These have been used in studies on specific components of suspended particulate matter such as lead (Azar et al., 1972) and they have wide application in assessing the exposures of individuals to pollutants, including sulfur dioxide, in industry, but they are not generally practicable for large-scale epidemiological studies on the general population.

A further problem in assessing exposures is the great variation in concentrations with time for, as far as sulfur dioxide is concerned, a brief exposure to a very high concentration, with no appreciable exposure during the rest of the day, would create a different situation from a steady exposure to a low level throughout the day. At present, there is no satisfactory way of measuring such situations, at least for people moving about during the course of the day. Providing studies are confined to groups of people living or working in reasonably uniform circumstances, measurements made over extended periods at a few fixed sites may give results that are valid for comparative purposes. Difficulties are liable to arise however if dissimilar groups are compared. In particular, people such as the very old and the very young may be partially protected from sulfur dioxide in the outside air if they spend long periods indoors, whereas an active worker may be exposed not only to a higher mean concentration in the course of the day, but also to a greater range. A further point is that increased activity will also lead to a greater ventilation rate, increasing the overall intake, and, in the case of sulfur dioxide, the deep inspirations associated with exercise are liable to increase the penetration of the gas and to enhance its effects (Lawther et al., 1975). The situation is even more complex for sulfuric acid aerosols. Because of the hygroscopic properties of the droplets, they take up moisture rapidly on inspiration, becoming larger and more dilute, and it has been suggested, on the basis of experimental work, that those from urban air could be diluted to such an extent that their irritant properties would be lost (Carabine & Maddock, 1976).

When assessing long-term exposures, annual mean concentrations at fixed sampling sites are commonly used as the basis. Short-term variations are then of little consequence, but it may still be necessary to consider the extent of seasonal swings in concentration, or the frequency of occurrence of days of exceptionally high pollution. Also, it is often necessary to examine trends in concentrations for many years back, for the relevant exposure may have been one that occurred earlier in life, rather than the current level. Since there are

very few long series of measurements of sulfur dioxide or suspended particulate matter made by uniform methods, it is very difficult to assess the true exposure of people to these pollutants.

6. ABSORPTION, DISTRIBUTION, AND ELIMINATION

Most of the sulfur compounds discussed in this report are absorbed via the digestive system. Relatively little is absorbed from the respiratory tract, even in areas with highly polluted ambient air. Even so, it is reasonable to believe that the respiratory tract is the most vulnerable organ for the local effects of sulfur oxides and particulate matter in the ambient air. Thus, this section will deal mainly with the absorption, deposition, and clearance of sulfur dioxide and particulate matter in the respiratory tract.

6.1 Absorption and Deposition in the Respiratory Tract

6.1.1 Sulfur dioxide

Sulfur dioxide is highly soluble in aqueous media. Absorption after inhalation has been studied in rabbits (Dalhamn & Strandberg, 1961; Strandberg, 1964), dogs (Balchum et al., 1959, 1960a, 1960b; Frank et al., 1969) and man (Speizer & Frank, 1966a, 1966b).

In rabbits, about 40% of the inhaled sulfur dioxide is absorbed in the nose and pharynx when concentrations of about 290 $\mu g/m^3$ (0.1 ppm) are inhaled. At higher concentrations (29-290 mg/m^3; 10-100 ppm), the fraction absorbed is much higher (about 95%). The reasons for these different rates of absorption are not clear. In dogs, more than 99% of the inhaled sulfur dioxide is absorbed by the nose at exposure levels of 2.9-140 mg/m^3 (1-50 ppm). These observations in dogs have been confirmed in man by studies on human volunteers, with levels of exposure to sulfur dioxide ranging from 2.9 to 420 mg/m^3 (1 to 140 ppm) and exposure times of a few minutes at the higher levels and 30-40 minutes at the lower levels. Absorption can occur during mouth-breathing, but is less efficient than during nose-breathing, especially with increased ventilation.

6.1.2 Airborne particles

Particles smaller than about 10 μm are deposited at different levels in the respiratory tract. The exact deposition pattern is determined by the interaction of size, shape, and density (expressed as aerodynamic diameter of unit density spheres) of the particles and by airflow conditions. Some particles in the air, such as sulfuric acid particles are hygroscopic. Such particles will take

up water, expand in the respiratory tract, and be deposited in a manner other than would be expected from their diameters in the ambient air (Hatch & Gross, 1964; Stuart, 1973; Task Group on Lung Dynamics, 1966; Vigdorčik, 1948). Sophisticated theoretical models for the deposition of particles in the lung such as the ICRP model have been constructed (Task Group on Lung Dynamics, 1966). Deposition is caused by impaction, sedimentation, and diffusion. Impaction is an important mechanism for the deposition of the larger or heavier particles (5-30 μm aerodynamic diameter) and where the air velocity is relatively high. Impaction occurs therefore at sites where the air stream is turbulent and is of most importance in the nose, mouth, pharynx, and the upper part of the tracheobronchial tree. Sedimentation or settling out of particles is also a function of particle size and density, as well as of residence time in the airways. It is important for the deposition of larger particles (1-5 μm) providing they have not been deposited by impaction and is active in the trachea, bronchi, and bronchioles. Diffusion is of importance for particles smaller than a few tenths of 1 μm (its effect increasing with decreasing particle size), with respect to the smaller bronchioles and especially the alveoli. In the size range of 2-5 μm, experimental data have fitted quite well with the ICRP model, but deposition has varied widely (with an order of magnitude of 2 to 3) among human subjects (Lippmann et al., 1971). In experiments on animals, large reproducible differences in deposition have been seen among individuals within the same species (Albert et al., 1968; Tomenius, 1973). In the submicron range, theoretical models have not yet been satisfactorily verified by experiments.

6.2 Clearance from the Respiratory Tract and Distribution

6.2.1 Sulfur dioxide

Sulfur dioxide is absorbed from the respiratory tract into the blood stream. It can then be widely distributed throughout the body (Balchum et al., 1960a, 1960b; Bystrova, 1957; Frank et al., 1967; Yokoyama et al., 1971), where it appears to be metabolized and excreted via the urinary tract.

6.2.2 Particulate matter

Knowledge concerning the elimination of insoluble particles deposited in the alveoli is incomplete (Hatch & Gross, 1964; Morrow, 1973). It is clear that these particles are, to a large extent, phagocytized by alveolar macrophages within hours, but it is not known to what extent they are actively carried to the ciliated part of the lung or to the lymphatic system. The particles can be transported by the mucociliary escalator into the interstitium (where they can remain for a long time) or the lymphatic system. Solubility *in vivo* is

important for the clearance of "insoluble" particles deposited in the alveoli (Mercer, 1967; Morrow, 1973). The biological half-lives range from days to years depending on the chemical composition of the particles (Brain & Valberg, 1974; Task Group on Lung Dynamics, 1966; Task Group on Metal Accumulation, 1973).

Mucociliary transport, and therefore clearance of particles, can be affected by various factors and can be impaired by long-term cigarette smoking and acute infection in the respiratory tract (Camner & Philipson, 1972; Camner et al., 1973a; Jarstrand et al., 1974). Subjects suffering from chronic obstructive lung disease may also have an impaired mucociliary transport (Camner et al., 1973b; Toigo et al., 1963). Studies in animals have shown that the inhalation of sulfur dioxide can interfere with the clearance of bacteria (Rylander et al., 1971) and inert particles (Ferin & Leach, 1973) from the lungs, but how much is due to the action of the sulfur dioxide on the mucociliary mechanism and how much to its action on the macrophages is not clear.

The clearance of soluble particles may follow the above pathways depending upon their solubility. They may dissolve in the mucus in which case they will probably be eliminated via the mucociliary route and be swallowed and removed or absorbed via the intestinal tract. In the alveoli, the particles may diffuse into the lymph or blood and thus be removed from the lung.

7. EFFECTS ON EXPERIMENTAL ANIMALS

It has been difficult to separate the relative effects of sulfur dioxide, sulfuric acid mists, sulfate salts, and particulate matter in the ambient air by epidemiological techniques. The effects of these substances individually and in various combinations have been studied in the laboratory. These studies have been useful in explaining some of the mechanisms of action but their application has been rather limited for the establishment of safe ambient levels, particularly for complex mixtures such as exist in the ambient air. In the past, the levels used in laboratory studies on animals have usually been far in excess of those seen in the ambient air and therefore have had little relevance for ambient air quality standards. Later studies have been at more relevant levels.

The following discussion separates work on animals into short-term and long-term exposure studies. Short-term exposure studies are those that involve exposures of 24-h or less and usually last from minutes to at the most a few hours. Long-term exposure studies refer to exposures that last longer than 24-h and are usually extended over months. In the short-term exposure studies, only immediate or acute effects have been studied. In long-term

exposure studies, animals may be studied during the period of exposure to determine whether there are progressive changes or not and at the end of the exposure period to quantify any chronic effect.

7.1 Short-term Exposure Studies

7.1.1 Exposure to sulfur dioxide singly or in combination with other agents

Sulfur dioxide is a respiratory irritant that is very soluble in the aqueous surfaces of the respiratory airways. Because of this high solubility, most of the sulfur dioxide is absorbed in the nose and upper airways (section 6.1) and very little reaches the lungs directly. At extremely high concentrations, the absorptive capacity of the upper airways can be overwhelmed and death or pathological changes including laryngotracheal and pulmonary oedema can be induced in the respiratory tract of experimental animals.

Exposure-effect curves have been developed for guineapigs (Amdur, 1966) and dogs (Frank & Speizer, 1965). In Amdur's study, a linear relationship was obtained between exposure for 1 h to sulfur dioxide concentrations ranging from 0.46 to 2380 mg/m^3 (0.16-835 ppm) and corresponding increases in pulmonary flow resistance. The second study showed that nasal flow resistance increased roughly in proportion to exposure to sulfur dioxide concentrations ranging from 20 to 660 mg/m^3 (7-230 ppm) for a 15-20 minute period.

Studies with guineapigs at lower concentrations have shown that a sodium chloride aerosol, administered concomitantly enhances the effects of sulfur dioxide on the lungs in the form of bronchoconstriction and increased airway resistance (Amdur, 1957). It was postulated that the sodium chloride could act as a carrier to deliver the absorbed sulfur dioxide deep into the lungs, or that the increased humidity in the respiratory tract could react with the sulfur dioxide to form sulfurous acid, especially if catalysts were present (Amdur & Underhill, 1968). McJilton et al. (1973) have reaffirmed the importance of humidity in this reaction, exposing guineapigs for 1 h to sulfur dioxide at 3.1 mg/m^3 (1.1 ppm) and a sodium chloride aerosol of about 1 mg/m^3. They allowed the mixture to "age" in a reaction chamber for 8-10 minutes at various relative humidities. The chamber temperature was 22°C and the average aerosol particle size was 0.1 µm with a maximum size of less than 2 µm. At relative humidities above 80%, they noted a marked increase in pulmonary resistance, whereas administration of the individual components produced little or no effect. The droplets formed at high humidity and in the presence of the aerosol had a pH of 3.2 ± 0.5. Analysis of these particles by mass spectrometer revealed sulfur dioxide and bisulfite ions (HSO^-_3) in the solution but no sulfuric acid. In the high humidity, the sodium chloride

aerosol apparently became hydrated and could then absorb sulfur dioxide. The authors indicated that the mixture had to "age" to ensure absorption of the sulfur dioxide; otherwise there would be too much competition with the moist surfaces in the nasopharynx which could sweep out the sulfur dioxide. Thus, this is another mechanism whereby the effect of sulfur dioxide can be enhanced. If such mixtures were allowed to "age" longer, it seems likely that the sulfur dioxide could be changed to sulfuric acid. Studies using other animal species such as the cat have not shown this enhancement of the effect of sulfur dioxide by sodium chloride (Corn et al., 1972).

Matsumura (1970a) exposed guineapigs to ozone at 2.1, 11, or 21 mg/m^3 (1, 5, or 10 ppm), nitrogen dioxide at 40, 80, or 140 μg/m^3 (20, 40, or 70 ppm), or sulfur dioxide at 60, 170, 510, or 940 mg/m^3 (20, 60, 180, or 330 ppm) for 30-50 minutes. Each group with unexposed controls was then exposed to an aerosolized antigen (2 μm) of egg albumin and bovine albumin for 45 minutes, 5-7 times at intervals of a day or more. Two weeks after the last exposure, the animals were killed and blood was drawn for assay of the immunological response. Enhanced sensitization was noted only at the highest levels of exposure. During these exposures a number of animals died of anaphylactic reactions at the fifth or sixth inhalation. In another study, sulfur dioxide at a concentration of 1100 mg/m^3 (400 ppm) did not have any effect on dyspnoeic attacks (Matsumura, 1970b).

7.1.2 Exposure to sulfuric acid aerosols or suspended sulfates

Sulfuric acid mist and some of the sulfate salts are more powerful respiratory irritants than sulfur dioxide, and this effect is also related to particle size (smaller particles tending to be more irritating) (Amdur, 1958). Treon et al. (1950) exposed rabbits, rats, mice, and guineapigs to sulfuric acid mist, 93-99% of which was less than 2 μm in diameter, many droplets being about 1 μm in diameter. Concentrations ranged from 87 to 1610 mg/m^3. Despite the relatively small number of animals used, a clear-cut species difference was shown at these high concentrations. The order of increasing sensitivity was rabbits, rats, mice, guineapigs.

It was reported by Amdur et al. (1952a) that the 8-h LC_{50} of sulfuric acid mist with a mass median diameter (MMD) of about 1 μm was 18 mg/m^3 for 1-2 month old guineapigs. Pattle et al. (1956) showed that sulfuric acid mist of MMD 2.7 μm was more toxic to guineapigs than a mist of 0.8 μm, and that the toxicity of the smaller particles increased when the exposure occurred at 0°C. However, this might be a response of the guineapig to low temperature rather than to the sulfuric acid mist. Concomitant exposures with ammonium carbonate had a protective action, apparently because it neutralized the sulfuric acid.

Table 11. Sulfuric acid and some sulfates in descending order of their irritative capacity for animals. Presented for equivalent amounts of sulfur and at comparable particle size i.e., sub-micron; short-term exposures [a]

Sulfuric acid	H_2SO_4
Zinc ammonium sulfate	$ZnSO_4(NH_4)_2\ SO_4$
Iron (III) sulfate	$Fe_2\ (SO_4)_3$
Zinc sulfate	$ZnSO_4$
Ammonium sulfate	$(NH_4)_2\ SO_4$
Nonreactive	
Iron (II) sulfate	$FeSO_4$
Manganese (II) sulfate	$MnSO_4$

[a] From: Amdur (1969, 1970, 1971).

Studies on guineapigs have shown that, for equivalent amounts of sulfur and in comparable particle size, sulfuric acid is more irritative than any of the sulfate compounds, some of which appear to be nonreactive in animals (Table 11). Whether these compounds would behave in the same manner in complex mixtures such as those found in polluted air is not known. Some of the nonreactive compounds such as manganese salts or oxides can catalyze the reaction of sulfur dioxide to sulfuric acid.

In short-term exposure studies by Amdur (1958), concentration seemed to be more important than duration and death was related to laryngospasm and bronchospasm. Sulfuric acid mist also caused parenchymal lung damage that seemed to be related to the total dose (Amdur, 1958; Pattle et al., 1956).

7.2 Long-term Exposure Studies

7.2.1 Exposure to sulfur dioxide

Rats were exposed for 96 days to sulfur dioxide at concentrations of 0.1, 0.5, and 1.5 mg/m^3 (0.04, 0.18 & 0.53 ppm). Histological examination showed interstitial pneumonia, bronchitis, tracheitis, and peribronchitis after exposures to the two higher levels (Elfimova & Gusev, 1969).

Misiakiewicz (1970) exposed rats continuously during 5 months to sulfur dioxide at concentrations of 0.3, 0.5, 1.0, 2.0, and 20.0 mg/m^3 (0.11, 0.18, 0.35, 0.7 and 7.0 ppm). Exposures to 2.0 mg/m^3 (0.7 ppm) and 20.0 mg/m^3 (7.0 ppm) increased the activity of serum cholinesterase (EC 3.1.1.8) and aspartate aminotransferase (EC 2.6.1.1) and caused morphological changes in the upper respiratory tract.

After a 120-h exposure to a sulfur dioxide concentration of 3 mg/m^3 (1.1 ppm), guineapigs showed proliferative interstitial pneumonia, bronchitis, and tracheitis and an increased histamine content in the lungs, while exposure

to 167 μg/m^3 (0.06 ppm) of sulfur dioxide for one month led to interstitial changes in the respiratory tract (Buštueva, 1961a). Buštueva (1966) also exposed rats for 65 days (24 h per day) to sulfur dioxide at 4.86 mg/m^3 (1.7 ppm). Tracheitis, desquamation of epithelial cells, an increased amount of purulent mucus, and interstitial pneumonia were found. It was not clear, however, whether this was due to the sulfur dioxide or to the pulmonary infection that can develop in rats.

Beagle dogs exposed to a sulfur dioxide concentration of 13.4 mg/m^3 (4.7 ppm) for 21 h per day, for 620 days, did not develop any specific histopathological changes (Lewis et al., 1973).

Guineapigs have been exposed to sulfur dioxide levels up to 16.3 mg/m^3 (5.7 ppm) for 12 months without definite effects except for slight cytoplasmic vacuolation in the liver (Alarie et al., 1970). Cynomolgus monkeys exposed continuously for 78 weeks to sulfur dioxide levels up to 3.7 mg/m^3 (1.3 ppm) did not show any significant pathological changes (Alarie et al., 1972). However, rats exposed to sulfur dioxide at 2.9 mg/m^3 (1 ppm) for 170 h showed a significant reduction in clearance of inert particles from the lung (Ferin & Leach, 1973). Syrian hamsters, made emphysematous by previous exposure to aerosolized papain, tolerated concentrations of sulfur dioxide up to 1900 mg/m^3 (650 ppm). Exposures were for 4 h per day, 5 days per week, for a total of 19-74 exposures. Only slight changes in the mechanical properties of the lung were noted as well as slight bronchitis (Goldring et al., 1970). As Syrian hamsters are exceptionally resistant to the effects of sulfur dioxide, these data must be extrapolated with caution to other species.

7.2.2 Exposure to sulfuric acid aerosols

Alarie et al. (1973) exposed cynomolgus monkeys for 78 weeks to sulfuric acid mist at concentrations of 0.38 to 4.79 mg/m^3 and particle sizes of 0.54 to 3.60 μm. At concentrations of 2.43 and 4.79 mg/m^3 and particle sizes of 3.60 and 0.73 μm, definite damage to the pulmonary structure was evident and there was deterioration in pulmonary function. At the lower concentrations, changes were slight or absent. The authors also exposed guineapigs for 52 weeks to concentrations of 0.08-0.1 mg/m^3 and particle sizes of 0.84 and 2.78 μm; no detectable effects were seen.

When beagle dogs were exposed to sulfuric acid at a concentration of about 0.9 mg/m^3 for 21 h per day, for 620 days, there was a significant reduction in pulmonary function; 90% of the sulfuric acid mist was less than 0.5 μm in diameter (Lewis et al., 1973). Histopathological changes were produced in the alveolar part of the lung, especially in the elastic tissue, of rats exposed for 65 days (24 h per day) to a sulfuric acid concentration of 1 mg/m^3. Ninety per cent of the particles were less than 2 μm in diameter in this study (Buštueva, 1966).

Guineapigs were exposed to sulfuric acid aerosol for 120 h at 3 different concentrations (1.98 ± 0.03; 4.20 ± 0.06; and 8.27 ± 0.15 mg/m^3). Exposure to the highest concentration led to oedema of the lungs, changes in the interalveolar walls, sharp, diffused, interstitial changes, and increased histamine content in the lung tissue. Three weeks after exposure, sclerosis appeared (Buštueva, 1957). After a 1-month exposure to 0.1 mg/m^3, no changes were found (Buštueva, 1961a).

7.2.3 Exposure to a mixture of sulfur dioxide and sulfuric acid aerosols or this mixture combined with other agents

Rats were exposed for 65 days (24 h per day) to a combination of sulfur dioxide at 4.86 mg/m^3 (1.7 ppm) and a sulfuric acid aerosol at 1 mg/m^3 (90% of the aerosol particles were less than 2 μm in diameter). There was a summation of the effects (histopathological changes in alveolar tissue) produced by exposure to each of the pollutants alone (Buštueva, 1966).

Lewis et al. (1973) exposed beagle dogs to a combination of sulfur dioxide at 13.4 mg/m^3 (4.7 ppm) and sulfuric acid at about 0.9 mg/m^3. Ninety percent of the sulfuric acid mist was less than 0.5 μm in diameter. The duration of exposure was 21 h per day, for 620 days. Some of the dogs had been pre-exposed to nitrogen dioxide. This group tended to show less response in the form of changes in pulmonary function than dogs not pre-exposed to nitrogen dioxide.

Alarie et al. (1975) exposed cynomolgus monkeys and guineapigs to mixtures of sulfur dioxide, fly ash, and sulfuric acid mist, for 18 months after an 8-week baseline period. Exposure concentrations varied from 0.29 to 143 mg/m^3 (0.1 to 5.0 ppm) for sulfur dioxide and from 0.1 to 1 mg/m^3 for sulfuric acid mist; the concentration of fly ash was approximately 0.5 mg/m^3. Particle size (MMD) varied from 0.53 to 3.11 μm in the acid mist and from 4.1 to 5.8 μm in the fly ash. Pulmonary function tests and serum biochemical and haematological analyses were conducted prior to, and periodically during, the exposure. Lungs were examined microscopically at the end of the experiment. Sulfuric acid mist appeared to be responsible for the effects observed. These were largely histopathological changes in the lungs. No synergistic action was noted between the pollutants.

7.2.4 Combined exposure to sulfur dioxide and particulate matter or other gaseous pollutants

In studies by Frazer et al. (1968), white albino rats were exposed to sulfur dioxide at 2.9 and 8.6 mg/m^3 (1 and 3 ppm) and graphite dust at 1 mg/m^3. The mean particle size of the dust was less than 1 μm and the MMD was 3 μm. The animals were exposed for 12 hours per day, 7 days per week, for 4

months. Both ciliary activity, and the number of dust-containing cells per 100 lung cells appeared to be unaffected after 56-109 days of exposure.

Various aerosols that may react with sulfur dioxide have been studied either singly or in combination with sulfur dioxide in experimental animals, particularly in guineapigs. Amdur (1969, 1971) emphasized that the particle size of the aerosol as well as the concentration was extremely important in the determination of toxicity and that the most important size range was the submicron level. The changes induced in pulmonary mechanics were slow to return to pre-exposure levels. This indicates either that deposited aerosols may not be cleared promptly but remain in the lungs exerting their effect for a period of time, or that the repair mechanisms are slow, or that both conditions are present. There was also a variation in the toxicity of different sulfates for the same particle size and sulfur content (Amdur, 1969) (Table 11).

Studies by Battigelli et al. (1969) in which rats were exposed to sulfur dioxide at 2.9 mg/m^3 (1 ppm) and graphite dust at 1 mg/m^3 (particle size not stated) did not show any effect other than the accumulation of dust in the lung after exposure for 4 months, for 12 hours per day. Amdur & Underhill (1968) pointed out that not all aerosols enhance the effect of sulfur dioxide and that only those aerosols composed of droplets in which the sulfur dioxide could dissolve were active.

Mice were exposed by Zarkower (1972) to carbon particles (1.8 to 2.2 μm MMD) at a concentration of 558 ± 154 μg/m^3 and sulfur dioxide at 5.7 mg/m^3 (2 ppm). The animals were exposed to carbon alone, carbon with sulfur dioxide, and sulfur dioxide alone; controls were unexposed. Killed *Escherichia coli* was used as an antigen and antibody production was measured. Exposures for 192 days produced significant immunosuppression. Shorter periods of exposure resulted in variable effects including stimulation of antibody production.

A variety of metallic aerosols can catalyze the oxidation of sulfur dioxide including the soluble salts of ferrous iron, manganese, and vanadium.

Rylander & Bergström (1973) exposed animals with latent upper respiratory disease and controls for 4 weeks to various combinations of sulfur dioxide at 57 mg/m^3 (20 ppm), manganese dioxide at 12-20 mg/m^3 (particle size between 5.0 and 0.5 μm), and carbon monoxide at 187-250 mg/m^3 (150-200 ppm). Animals with latent upper respiratory disease showed more extensive histological changes and an increase in the number of free lung cells. The combination of sulfur dioxide and manganese dioxide produced the greatest changes.

An addition of effects in rats was reported by Šalamberidze (1969) from joint exposure to sulfur dioxide at 0.15 mg/m^3 (0.05 ppm) and nitrogen dioxide at 0.1 mg/m^3 (0.05 ppm) over a 3-month period.

The precise mechanism by which the oxides of sulfur and particulate

matter can affect the lungs is not known. Sulfur dioxide (and presumably sulfuric acid as well) can interfere with the clearance of bacteria (Rylander et al., 1971) and inert particles (Ferin & Leach, 1973) from the lungs (see also section 6). Chronic exposure to sulfur dioxide increased the number and area of goblet cells in guineapigs and lambs (Mawdesley-Thomas et al., 1971).

The considerable variations in the results of these experiments on animals reflect differences in sensitivity of individual species, exposure levels, and methods used to assess the effects.

It should be emphasized that extrapolation of these results from animals to human beings is not easy. These findings, however, do give some insight into possible mechanisms of action and reactions that can occur.

8. EFFECTS ON MAN

8.1 Controlled Exposures

A number of studies have been performed on volunteers under controlled conditions of exposure to sulfur dioxide or sulfuric acid aerosols, singly or in combination, or to mixtures of these with other compounds such as ozone and hydrogen peroxide. These studies, all conducted under short-term exposure (up to 24 h), include those on changes in respiratory function and effects on sensory and reflex organs.

8.1.1 Effects on respiratory organs

8.1.1.1 *Exposure to sulfur dioxide*

Amdur et al. (1953) exposed 14 healthy volunteers (inhaling through the mouth) to sulfur dioxide at concentrations of 2.9-23 mg/m^3 (1-8 ppm) for 10 min. They noted an increased pulse frequency, decreased tidal volume, and an increased respiratory frequency which returned to normal levels after exposure. The sequence of exposures was randomized. Effects increased with increasing levels of sulfur dioxide and were detectable at the lowest concentration tested (2.9 mg/m^3; 1 ppm). Sulfur dioxide levels were monitored by the conductimetric method. However, Lawther (1955) was unable to reproduce these effects in any consistent manner, either in urban or in rural dwellings. Eleven healthy volunteers were exposed to sulfur dioxide at levels of 2.9, 14, and 37 mg/m^3 (1, 5, and 13 ppm) in studies by Frank et al. (1962). Respiratory mechanics were measured by means of a body plethysmograph and an oesophageal balloon. Exposures lasted 10-30 min. Only one of the 11 subjects exposed showed an increased pulmonary resistance at 2.9 mg/m^3 (1 ppm). Increased pulmonary resistance was noted in all subjects and was greater at

the higher concentration. The change occurred within 1 min of exposure and increased up to 10 min, after which no further increase was noted.

In studies by Snell & Luchsinger (1969), exposure to a sulfur dioxide concentration of 2.9 mg/m^3 (1 ppm) for 15 min produced a slight effect on total respiratory resistance in 9 healthy volunteers.

Andersen et al. (1974) exposed healthy male subjects to sulfur dioxide at levels of 2.9, 14, and 71 mg/m^3 (1, 5, and 25 ppm) for up to 6 h. With exposures of 1-3 h at 2.9 mg/m^3 (1 ppm), there was a decrease in the flow of nasal mucus and a decrease in the cross section of the nasal passages. Thus it appears that exposure to concentrations of 2.9 mg/m^3 (1 ppm) or more may result in impairment of mucociliary transport in the nose.

Four healthy volunteers were exposed to sulfur dioxide and the forced vital capacity (FVC), one second forced expiratory volume ($FEV_{1.0}$), mid-maximal flow rates (MMFR), maximal expiratory flow rate at 50% ($MEFR_{50}$) and closing volume and capacity were measured. Although no changes were found in these tests at 1.1 mg/m^3 (0.37 ppm), slight changes in FVC, $FEV_{1.0}$, MMFR, and $MEFR_{50}$ were noticed at 2.1 mg/m^3 (0.75 ppm) after exposure for 30 min; no effect on closing volume was detected (Bates & Hazucha, 1973).

The results of these studies on human volunteers are summarized in Table 12.

Table 12. Selected laboratory studies on the effects of short-term exposures to sulfur dioxide on respiratory function in volunteers

Concentration (mg/m^3)[a]	Concentration (ppm)	Length of exposure (min)	Effects	Subjects	Reference
2.9-23	1-8	10	Increased pulse rate, decreased tidal volume, and increased respiratory rate	14 healthy males	Amdur et al. (1953)
2.9	1	10-30	Increased pulmonary resistance	11 healthy males	Frank et al. (1962)
2.9	1	15	Increased respiratory resistance	9 healthy subjects (5 males & 4 females)	Snell & Luchsinger (1969)
2.9	1	60-180	Decreased nasal mucus flow and decreased cross section of nasal passages	15 healthy males	Andersen et al. (1974)
2.1	0.75	120	Slight effect in 30 min on FVC, $FEV_{1.0}$, MMFR, and $MEFR_{50}$; no effect on closing volume	4 healthy subjects	Bates & Hazucha (1973)
1.1	0.37	120	No effect on above tests of pulmonary function throughout exposure period	4 healthy subjects	Bates & Hazucha (1973)

[a] Original levels reported as ppm have been converted to mg/m^3 and rounded off.

8.1.1.2 *Exposure to sulfuric acid aerosols*

Amdur et al. (1952b) exposed 15 healthy men to sulfuric acid mist, through mouth breathing, at concentrations of 0.35-5 mg/m^3 (particle size of

approximately 1 μm) for periods of 5-15 min. At concentrations below 1 mg/m^3, the mist did not produce any subjective sensations although 5 of the 15 subjects showed a slightly increased respiratory rate and a decreased tidal volume at 0.35 mg/m^3. All subjects noted irritation at a concentration of 3 mg/m^3. Respiration was monitored by means of a pneumotachograph. The respiratory changes as well as the subjective sensations increased with increasing concentrations of sulfuric acid. Healthy male volunteers were also exposed to sulfuric acid mist by Sim & Pattle (1957), either by mask or in a chamber for periods ranging from 10 to 60 min. Twelve men were exposed to the mist. The temperature of the air was 18.4°C with a relative humidity of 62%. The MMD of the aerosol was 0.99 μm and the concentration was 39.4 mg/m^3. The men noted minor irritation, and lung resistance (as measured by the interrupter technique) rose by 35-100%. With re-exposure for 30 min to the mist at a temperature of 24.5°C, a relative humidity of 91%, a concentration of 20.8 mg/m^3, and a MMD of 1.54 μm, severe coughing and irritation of the throat occurred. The men found it almost intolerable. Lung resistance had risen by 43-150% when measured after 10 minutes of exposure and when coughing had ceased. No changes in respiration, blood pressure, or pulse rate were noted. Two of the men exposed to these conditions had persistent symptoms for some days after exposure ended.

It is difficult to evalute these two studies. Amdur did not report the temperature, though it was probably in the neighbourhood of 24°C, or the relative humidity. The studies of Sim & Pattle were at relatively high levels but they demonstrated the importance of the relative humidity or perhaps even more important, the absolute humidity. The results of these studies are summarized in Table 13. None of these studies used sulfates.

Table 13. Selected laboratory studies on the effects of short-term exposures to sulfuric acid mist on respiratory function in volunteers

Concentration (mg/m^3)	Particle Size (μm)	Length of exposure (min)	Relative Humidity (%)	Temperature (°C)	Effects	Subjects	Reference
0.35	1	5-15	?	Room (?24)	5 of 15 subjects increased respiratory rate and decreased tidal volume	15 healthy subjects	Amdur et al. (1952b)
39.4	0.99	60	62	18.4	Increased pulmonary resistance and minor irritation	12 healthy males	Sim & Pattle (1957)
20.8	1.54	30	91	24.5	Marked increase of pulmonary resistance and severe irritation	12 healthy males	Sim & Pattle (1957)

8.1.1.3 *Exposure to mixtures of sulfur dioxide and other compounds*

Frank et al. (1964) repeated the above exposures in combination with a sodium chloride aerosol. Concentrations of sulfur dioxide were: 2.9-5.7 mg/m^3 (1-2 ppm), 11-17 mg/m^3 (4-6 ppm), and 40-49 mg/m^3 (14-17 ppm). The sodium chloride aerosol had a geometric mean diameter of 0.15 µm with a geometric standard deviation of 2.3 µm and an average concentration of 18 mg/m^3. As in the earlier studies, little change in pulmonary flow resistance was noted at the lower levels of sulfur dioxide alone (2.9-5.7 mg/m^3; 1-2 ppm) but a progressive increase was noted at higher levels. The authors did not find any systematic differences between the responses to sulfur dioxide alone or to the gas plus the aerosol. As mentioned in section 8.1.1.1, Snell & Luchsinger (1969) noted a slight effect of sulfur dioxide at 2.9 mg/m^3 (1 ppm) on total respiratory resistance but could not demonstrate an enhancing effect of either a sodium chloride aerosol or a distilled water aerosol. Burton et al. (1969) exposed volunteers to a concentration of sulfur dioxide of 6 mg/m^3 (2.1 ppm) with or without a sodium chloride aerosol (MMD of less than 0.4 µm) at a concentration of 2.2 mg/m^3. The inhaled air was warmed and moistened. However, they too failed to demonstrate any effect of the sodium chloride aerosol on the response to sulfur dioxide.

Thus, three groups have not been able to demonstrate any enhancing effect of sodium chloride aerosol on respiratory resistance in man as had been demonstrated in guineapigs. This does not exclude the possibility that other particulate matter might enhance the effect of sulfur dioxide on the human respiratory system. These studies should be repeated at levels of humidity above 80% and the mixture should be allowed to "age".

The possible interaction of sulfur dioxide and hydrogen peroxide has been examined by Toyama & Nakamura (1964) and that of sulfur dioxide and ozone by Bates & Hazucha (1973). Toyama & Nakamura (1964) studied 24 healthy male volunteers by means of a pneumotachograph and the interrupter technique to measure alveolar pressure; airway resistance was determined from these measurements. The particle sizes of the hydrogen peroxide were reported to be 1.8 and 4.6 µm. Concentrations of hydrogen peroxide were 0.8-1.4 mg/m^3 for the larger particles and 0.01-0.1 mg/m^3 for the smaller ones. Levels of sulfur dioxide ranged from 2.9 to 170 mg/m^3 (1-60 ppm). The subjects were not aware whether they were breathing hydrogen peroxide, sulfur dioxide, or combinations. It was not stated whether the order of administration was randomized or not. The investigators noted a marked increase in airway resistance with the mixture compared with the individual components. They also noted that the larger particles had more effect than the smaller particles. This was probably due to the greater dose delivered, although they did not comment on this. It was the authors' opinion that the

enhancement of the response to the combination was due to the conversion of sulfur dioxide to sulfuric acid, although no measurement for sulfuric acid was made.

In similar studies by Bates & Hazucha (1973) healthy male volunteers were exposed in a chamber to sulfur dioxide, or ozone, or a combination of the two. Changes in FVC, $FEV_{1.0}$, MMFR, MEFR at 50% vital capacity and peak expiratory flow rates were studied and some effects were noted during exposure to ozone at 540-1610 $\mu g/m^3$ (0.25-0.75 ppm). Sulfur dioxide by itself had little effect over a similar range. Joint exposure to sulfur dioxide and ozone at 1060 $\mu g/m^3$ (0.37 ppm) and 790 $\mu g/m^3$ (0.37 ppm), respectively, produced a greater effect than ozone alone. Changes were noted after exposure for 30 min and were marked after 2 h of exposure. Exercise during exposure enhanced the effect.

8.1.2. Effects on sensory or reflex functions

Studies in the USSR have concentrated on the effects of sulfuric acid aerosols and sulfur dioxide on sensory receptors, cerebral cortical function, and their interrelationships. When sulfuric acid mist produced subjective sensory stimulation such as odour or irritation of mucous membranes, or both, then, invariably, objective evidence of central nervous system depression could be demonstrated (Rjazanov, 1962).

Buštueva (1961b) did not note any change in optical chronaxy in volunteers exposed to concentrations of sulfur dioxide of 0.5 mg/m^3 (0.18 ppm) and sulfuric acid of 0.3 mg/m^3. However, when levels of 1.5 mg/m^3 for sulfur dioxide, 0.73 mg/m^3 for sulfuric acid, and combined levels of 1.2 mg/m^3 and 0.6 mg/m^3, respectively, were exceeded, optical chronaxy increased (Table 14). Similar effects were seen in dark adaptation responses (Rjazanov, 1962).

Studies have also been carried out in which the cerebral cortex was monitored by electroencephalography. Alpha rhythm suppression was used as an index of response. Threshold levels at which a response was noted are given in Table 14. (Buštueva et al. 1960).

The electrocortical conditioned reflex is a central nervous system phenomenon elicited only after a succession of repeated, conditioned reflex trials. After exposure to a combination of irritants (sulfur dioxide or sulfuric acid) and light has been repeated several times, desynchronization begins to appear before the light is switched on. This can be produced at levels generally not sensorially perceived. Thus, unperceived odour or stimulus appears to become the conditioning stimulus and generates the conditioned electrocortical reflex (Rjazanov, 1962).

Table 14. Threshold levels of sulfur dioxide and sulfuric acid required for effects on sensory or reflex functions in volunteers during short-term exposures[a]

Effects	Threshold levels (mg/m^3)		
	Sulfuric acid	Sulfur dioxide	Sulfuric acid + Sulfur dioxide
Perception of odour and irritation of mucosa	0.6 to 0.85	1.6 to 2.8	0.3 + 0.5
Suppression of dark adaptation	0.63 to 0.73	0.92	0.3 + 0.5
Elevation of optical chronaxy	0.73	1.5	0.6 + 1.2
Disruption of alpha rhythm	0.63	0.9	0.3 + 0.5
Conditioning of electrocortical reflex	0.4	0.6	0.15 + 0.5 or 0.3 + 0.25

[a] Summarized from studies in the USSR (Buštueva, 1961b; Buštueva et al., 1960; Rjazanov, 1962).

Elfimova & Hačaturjan (1968) exposed volunteers to sulfur dioxide, phenol, and carbon monoxide and noted a summation of effects as measured by reflex action. No interaction was noted between sulfur dioxide at 0.5 mg/m^3 (0.18 ppm) and carbon monoxide at 3 mg/m^3 (2.4 ppm) as measured in volunteers by the sensory reflex technique (Mamacašvili, 1968).

8.2 Industrial Exposure

Workers are exposed to sulfur dioxide or sulfuric acid mist in a number of industries; sometimes exposure is not solely to sulfur dioxide or sulfuric acid. Exposed populations have been studied with respect to the effects of exposure on their health status or on their respiratory system. However, in many of these studies, only the currently employed workers were examined and a serious effort was not made to locate subjects who had left the industry and who may have suffered more from the disease or could have been more sensitive to the materials. It should also be emphasized that, in general, in the following reports, the exposure levels studied were from spot samples or for very short time intervals.

8.2.1 Exposure to sulfur dioxide singly or in combination with particulate matter

Kehoe et al. (1932) studied men working in a refrigerator company in the USA where sulfur dioxide was the refrigerant. Exposures averaged 60-90 mg/m^3 (20-32 ppm) with peaks as high as 200 mg/m^3 (70 ppm). These peaks had probably been higher in the past ranging up to 290 mg/m^3 (100 ppm) or more. The exposed group had significantly more respiratory symptoms and colds. They also complained more of fatigue and shortness of breath on

exertion. Chest X-rays of the exposed and unexposed groups showed the same distribution of abnormalities. The authors concluded on their inadequate evidence that there was no injury to the tracheobronchial tree or alveoli.

In studies on men working in smelters in Sweden, Sjörstrand (1947) found that those who had worked at the roasting and reverberatory furnaces and in the converter hall for 8 years or more had poorer respiratory function than men working in other parts of the smelter. Levels of exposure and the smoking histories of the subjects were not reported. Men working in smelters are exposed to a variety of dusts as well as to sulfur dioxide and it is difficult to separate the effects of such exposures from those due to sulfur dioxide.

Men exposed to sulfur dioxide at daily mean concentrations up to 70 mg/m^3 (25 ppm) with occasional peaks of 290 mg/m^3 (100 ppm) in certain areas of a petroleum refining plant in Abadan (Iran) were compared by Anderson (1950) with an unexposed group. No differences were found between the two groups. This study also did not refer to the smoking histories of the subjects.

In a study in Norway, pulp mill workers were compared with paper mill workers using a standard questionnaire on respiration and simple tests of pulmonary function. The smoking histories of the subjects were also studied. Levels of sulfur dioxide ranged from 6-100 mg/m^3 (2-36 ppm) with peaks of 290 mg/m^3 (100 ppm) when the digester was blown. The exposed group had more cough, sputum, and dyspnoea than the unexposed group but the vital capacities were similar in both groups. The expiratory peak flows, however, of the exposed men under 50 years of age were lower than those in a comparable unexposed group (Skalpe, 1964).

A similar study was carried out in the USA by Ferris et al. (1967) who reported that there was no difference between men in a pulp mill and men in a paper mill. Both groups had less respiratory disease than was reported from a survey of the general population. The authors noted that some of the men working in the paper mill had worked in the pulp mill but had left because they could not tolerate the conditions. Occupational levels of exposure to sulfur dioxide ranged from a trace to 95 mg/m^3 (33 ppm). Average levels ranged from 6 to 35 mg/m^3 (2-13 ppm). Smoking habits were considered.

Huhti et al. (1970) studied pulp and paper mill workers in Finland and noted that the effects of smoking were much more significant than the exposures at work or the effects of climate. Levels of exposure were not reported in this study.

Men working in two integrated steel mills in Wales were studied by Lowe et al. (1968, 1970) and Warner et al. (1969). Mean concentrations of sulfur dioxide over 3 years ranged from 1.8 to 2.1 mg/m^3 (0.6 to 0.7 ppm) and those of suspended particulate matter in the respirable range, ranged from

600 to 1800 $\mu g/m^3$ (by elutriation technique). Analysis of the particulate matter showed that it was mainly composed of iron oxides and calcium sulfate. No effects on respiratory symptoms or on simple tests of pulmonary function were found after standardization for cigarette smoking and for age. These observations may reflect the limitation of studying occupational groups because of the effect of the selection processes, or this may be an example in which the suspended particulate matter present was not interacting with the sulfur dioxide to produce an effect.

8.2.2 Exposure to sulfuric acid mist

Dorsch (1913) studied men exposed to sulfuric acid mist in a plant manufacturing storage batteries in Germany. He reported that at a concentration of 0.5 mg/m^3, the mist was barely noticeable; at 2.0 mg/m^3, there was nose and throat irritation, at 3-4 mg/m^3, there was distinct discomfort, and at 6-8 mg/m^3, there was marked discomfort. These responses are comparable to those reported in laboratory studies on human beings in section 8.1. No particle size was given but, as noted in another survey reported below, they were probably relatively large.

Men in the battery industry were also examined by Malcolm & Paul (1961) in the United Kingdom who reported that there was significant erosion of the teeth of the battery room workers. This was confirmed by ten Bruggen Cate (1968). Apparently this was due to the direct impingement of relatively large droplets of sulfuric acid on the teeth.

Williams (1970) studied men from the same works as Malcolm & Paul (1961) and reported that there was no difference in the forced vital capacity and the one-second forced expiratory volume between the men in the forming and control departments. Levels of sulfuric acid mist averaged 1.4 mg/m^3 during working hours over two days and ranged from a trace to 6.1 mg/m^3 in 1968. An earlier survey reported higher values. Particle size reported from a survey in another forming department doing comparable work was 14 μm MMD; 4% of the particles being less than 4 μm MMD. The level of sulfuric acid in this department was 2.7 mg/m^3.

8.3 Community Exposure

Much of the information that has been gained concerning the effects on health of exposure to realistic concentrations of sulfur oxides and particulate matter has come from epidemiological studies, carried out on segments of population chosen by virtue of place of residence, age, existing state of health, or other characteristics, in order to present contrasts in exposure or sensitivity to these pollutants. Some studies have been based on the complete populations of urban areas, observing the total number of deaths, or the incidence or prevalence of illness within them in relation to differences in

pollution between areas, or with time in any one area.

Many epidemiological studies concerning the health effects of exposure to sulfur oxides and particulate matter have been reported in the literature. In the discussion that follows, attention has been directed to papers that yield information relevant to the development of exposure-effect and exposure-response relationships for sulfur oxides, smoke, and suspended particulate matter, and to some others that are of interest from the point of view of the method of approach.

8.3.1 Mortality – effects of short-term exposures

The most clearly defined effects on mortality arising from exposure to sulfur oxides and particulate matter have been the sudden increases in the number of deaths occurring, on a day-to-day basis, in episodes of high pollution. The most notable of these occurred in the Meuse Valley in 1930 (Firket, 1931), in Donora in 1948 (Schrenk et al., 1949), and in London in 1952 (Ministry of Health, UK, 1954). The people primarily affected were those with pre-existing heart or lung disease or both, and the elderly. The London episode lasted for 5 days and it was estimated that the number of deaths during and immediately after this period was about 4000 more than expected under normal circumstances. On one day, the number of deaths was about three times the number expected at that time of the year. Concentrations of sulfur dioxide as high as 3.7 mg/m^3 (1.3 ppm) were recorded in the centre of the urban area (48-h average). Concentrations of particulate matter were too great to be measured properly (British daily smoke/sulfur dioxide method), and the 48-h average of about 4.5 mg/m^3 at a central site must be regarded as a conservative estimate. These were rough estimates for the exposures and, probably, there was considerable variation in individual exposures.

Following these major episodes, attention was turned to studies on more moderate day-to-day variations in mortality within large cities, in relation to pollution. Gore & Shaddick (1958) correlated mortality in the County of London (the inner part of the Greater London Area) with pollution by smoke and sulfur dioxide for 4 foggy periods in 1954-56, using 7-day moving averages to smooth out the data. The authors considered that, in two of the episodes, there was a marked increase in mortality from bronchitis and other lung diseases, particularly in the elderly. They concluded that when the 24-h mean concentration of smoke exceeded 2.0 mg/m^3 at the same time as the 24-h mean concentration of sulfur dioxide exceeded 1.1 mg/m^3 (0.4 ppm) (British daily smoke/sulfur dioxide method), there would be increased mortality. Care was taken in this study to ensure that the measurements were reasonably representative of the exposure of people anywhere within the study area: the figures quoted were the mean values from a group of 7 sites, all situated close

ground level in mainly residential areas. However, there remained the problem that the people at risk in a study of this type were the elderly sick, who were likely to remain indoors, and that outdoor measurements might not have provided an adequate assessment of exposure (Biersteker et al., 1965).

The relationship between daily mortality in the more extensive area of Greater London and day-to-day variations in pollution (smoke and sulfur dioxide) and visibility was examined by Martin & Bradley (1960) in the winter of 1958-59. They noted that on days when the smoke concentration increased by more than 100 μg/m³ compared with the previous day, or when the sulfur dioxide concentration increased by 70 μg/m³ (0.025 ppm), there was likely to be increased mortality (British daily smoke/sulfur dioxide method). The increases in daily mortality were up to about 1.25 times expected values assessed from 15-day moving averages. Thick fog (visibility less than 200 metres) was also associated with increases in mortality. The relative importance of the 3 factors could not be determined but, on the basis of other work, the authors considered that the smoke was probably the most important. It is not clear whether the results are best interpreted in terms of change in pollution from one day to the next, rather than in terms of absolute values, but there is support for the former approach from studies carried out elsewhere. When results were considered on an absolute basis (Lawther, 1963), it was concluded that increases in mortality became evident when the 24-h mean concentrations of smoke and sulfur dioxide exceeded 750 μg/m³ and 710 μg/m³ (0.25 ppm), respectively. The measurement sites were the same as those used by Gore & Shaddick (1958). They could still be considered reasonably representative of outdoor concentrations in the areas where people lived, although the inclusion of outer, less-densely populated areas meant that the average exposures would tend to have been underestimated.

Studies on day-to-day variations in mortality in London were continued in successive winters, and coupled with the records of emergency hospital admissions. In a later paper, Martin (1964) showed correlations between both the daily mortality and hospital admission data and concentrations of smoke or sulfur dioxide. There was no clearly defined level above which effects were seen, but there were fairly consistent increases in both mortality and hospital admissions when the concentrations of smoke and sulfur dioxide each exceeded a 24- mean of about 500 μg/m³ (0.18 ppm of sulfur dioxide, British daily smoke/sulfur dioxide method). In 1962, there was a major episode of high pollution in London, similar in terms of duration and of sulfur dioxide concentrations to the one in 1952, but with lower smoke concentrations. Again, there was a sudden increase in deaths, but the number of deaths was not as great as before (about 700, compared with 4000). Whether the change in medical care could have influenced these results is not clear. The greater use of antibiotics in 1962 compared with 1952 might have reduced the

number of deaths, and a greater awareness of the risk together with clear advice to the elderly and infirm to remain indoors could have had an effect. The dramatic reduction in smoke concentrations in London brought about by the implementation of the Clean Air Act, and the more gradual reduction in sulfur dioxide that has followed it, have meant that in more recent years there have been few occasions when levels of 500 $\mu g/m^3$ have been exceeded simultaneously for smoke and sulfur dioxide (Waller et al., 1969).

Biersteker (1966) published a study of an episode of high pollution in Rotterdam in December 1962, when concentrations of smoke and sulfur dioxide of approximately 500 $\mu g/m^3$ and 1000 $\mu g/m^3$ (0.35 ppm), respectively, were recorded (24-h means, OECD smoke/sulfur dioxide method). There were increases in admissions to local hospitals of people over 50 years of age with cardiovascular diseases, and there was also some indication of an increase in mortality. This was observed only once in Rotterdam and could have been due to other causes. Further observations during a similar episode would be needed to provide a convincing statistical relationship between hospital admissions and these levels of pollution.

A relationship between day-to-day changes in mortality and pollution has also been reported from Osaka (Watanabe 1966). There appeared to be increases in mortality (about 20%) on days when the concentration of suspended particulate matter (light scattering method) exceeded 1 mg/m^3 (4-day average) and was associated with a level of sulfur dioxide of 200 $\mu g/m^3$ (0.07 ppm). Low temperatures may have been partly responsible for the effects.

Variations in daily mortality in New York in relation to sulfur dioxide concentrations were studied by Buechley et al. (1973). They examined correlations and developed regressions between a number of daily climatic factors and indices of pollution (sulfur dioxide, conductimetric method and coefficient of haze (Cohs)), and the mortality residuals for a given day. They noted that the day of the week had a special correlation with mortality (mortality rates were considerably higher on Mondays). Regression analysis indicated that heat waves and seasonal cycle were major predictors of mortality. Other factors were much weaker (about one third as strong) but were all of equal strength. Partial residual mortality values were computed and showed a significant correlation with the levels of air pollution (sulfur dioxide $r = 0.14$). Mortality could be predicted equally as well from Cohs as from sulfur dioxide levels. Mortality was 1.5% less than expected on 232 days when sulfur dioxide levels were below 30 $\mu g/m^3$ (0.01 ppm) and 2% greater than expected on 260 days when the sulfur dioxide levels were above 500 $\mu g/m^3$ (0.18 ppm) after correcting for the other factors. The crossover point (i.e., that point below which deaths were less than expected and above which deaths were greater than expected) was in the vicinity of a concentration of sulfur dioxide of 260 $\mu g/m^3$ (0.09 ppm). On the other hand, the data from

these studies could be interpreted to show a continuum of an effect across the levels of sulfur dioxide, which, in turn, should not be considered the causative agent but rather an index of pollution.

Schimmel & Murawski (1975) have reported on their regression analysis of daily deaths and levels of pollution (smoke shade and sulfur dioxide) in New York City for 1963-1972. This was an extension of an earlier study (Schimmel & Greenberg, 1972). The authors controlled for season, day of week, and temperature. During this time there was a marked reduction in the average level of sulfur dioxide from 510 $\mu g/m^3$ (0.18 ppm) to 170 $\mu g/m^3$ (0.06 ppm) but virtually no change in smoke shade. Their observations indicated that, despite this reduction in sulfur dioxide, there had been no reduction in adverse health effects. Analysis indicated that the adverse health effects were associated principally (80%) with the particulate matter and only to a small extent (20%) with the sulfur dioxide. However, the authors also pointed out that, when they regressed mortality on temperature and sulfur dioxide alone, the effects attributable to the sulfur dioxide increased three-fold.

These findings are provocative but they must be interpreted cautiously because of a number of limitations in the data. Air pollution levels were from data obtained at a single monitoring station and were probably not truly representative of exposures for the community. The standard errors reported with their data are large. The report should be considered to be an indicator for further studies in which age-specific death rates and causes of death should be included in the analysis as well as more relevant air pollution measurements. The results should not be used for developing an exposure-effect relationship.

A study involving comparisons between daily mortality data in New York and Tokyo was carried out by Lebowitz et al. (1973). They applied a "stimulus-response" technique to identify associations between days of high pollution and days with increased mortality, and showed strong relationships in both cities. However, their findings do not provide information of direct value in the assessment of exposure-effect relationships.

8.3.2 Mortality – effects of long-term exposures

In countries having reliable systems for the collection and analysis of data on deaths, based on cause and area of residence, death rates for respiratory diseases have commonly been found to be higher in towns than in rural areas. Many factors, such as differences in smoking habits, occupation, or social conditions may be involved in these contrasts, but, in a number of countries, a general association between death rates from respiratory diseases and air pollution has been apparent for many decades.

Analyses of these data have been of great value as a lead for

epidemiological studies, but the absence of information concerning other relevant variables, such as smoking, and the relatively crude nature of the indices of pollution used in many of these studies make them unsuitable for the assessment of exposure-effect relationships.

The studies of Daly (1954, 1959), Pemberton & Goldberg (1954), and Stocks (1959) were all based on mortality data from towns in England and Wales, and each showed a positive correlation between bronchitis or pneumonia death rates and some index of pollution by sulfur oxides or particulate matter, as assessed for periods close to those for which death rates were calculated. The most detailed investigation of this type, taking into account social factors as well as pollution, but still not smoking, was that conducted by Gardner et al. (1969). One interesting feature of their findings was a slight improvement in correlation when the index of pollution used was related to a period some 10 years earlier than that for which the death rates were calculated (deaths 1958-64, pollution index 1952). This illustrates another of the problems that has been widely recognized when trying to use mortality records to assess the effects of pollution i.e., that it may not be recent exposures that are most relevant, but those earlier in life; where concentrations have changed markedly over the years, current measurements may not provide an adequate index.

Lave & Seskin (1970) reanalyzed some of the mortality data from England and Wales, and developed multiple regression equations in terms of pollution and socioeconomic indices. Again their findings of positive correlations with pollution are of general interest but cannot contribute to the development of dose-response relationships. These authors also examined analogous data for Standard Metropolitan Statistical Areas (SMSAs) in USA and in a later paper (Lave & Seskin, 1972) they attempted to assess the relative effects of air pollution, climate, and home heating on mortality rates. Although equations were obtained relating death rates to measurements of suspended particulate matter and total sulfates (both by high volume sampler), it is doubtful whether these can be regarded as valid in the absence of adequate information on smoking.

8.3.3 Morbidity – effects of short-term exposures

Prospective studies on specific occupational groups, not professionally exposed, can be useful in assessing the effects of air pollution in different communities or in areas where a change in air pollution is expected. In such studies, where respiratory diseases are followed, it is necessary to control for age distribution and household composition, and to employ adequate statistical methods. In studies on the Philadelphia area, USA, Dohan & Taylor (1960) used absences of seven days or more because of respiratory disease as the

ndex and related this to the levels of sulfate. A later report by Dohan (1961) ted that this relationship was stronger during an epidemic of influenza. en et al., (1969) repeated this type of study in the same area on a slightly different occupational group using more detailed statistical analyses. They ere not able to confirm the earlier observations that the sulfate levels were lated to absences due to respiratory diseases.

Results have been reported (Lawther et al., 1970) of a series of studies extending from 1954 to 1968 that were carried out mainly in London, but also in some other large cities in England, using a diary technique for the self-assessment of day-to-day changes in conditions among bronchitic patients. A daily illness score was calculated from the data contained in the diaries and this was related to the concentrations of smoke and sulfur dioxide (British daily smoke/sulfur dioxide method) and to weather variables. The pollution figures used for most of the London studies were the mean values from the group of sites associated with the mortality/morbidity studies of Martin (1964) and Gore & Shaddick (1958). Many of the subjects in the series were active enough to be out and about and at work, and the measurements were considered to give a reasonable assessment of the average exposures in the areas where they lived or worked. The method used in these studies has not been validated, for the subjects recorded only their own assessment of their condition, and this was not checked against regular clinical examinations or ventilatory function measurements, but the changes appeared to have some real meaning. In the earlier years of the series, when the general level of pollution was high, well defined peaks in the illness score were seen when concentrations of either smoke or sulfur dioxide exceeded 1000 $\mu g/m^3$. With the reductions in pollution that followed the gradual implementation of the Clean Air Act, these changes in condition became less frequent and of smaller magnitude, and the conclusion from the series as a whole, up to 1968, was that the minimum pollution associated with significant changes in the condition of the patients was a smoke level of about 250 $\mu g/m^3$ together with a sulfur dioxide concentration of about 500 $\mu g/m^3$ (0.18 ppm) (24-h means, British daily smoke/sulfur dioxide method). At these levels, there was still some evidence that the peaks were associated specifically with pollution rather than with adverse weather conditions. A later study that has been reported by Waller (1971), showed that, with much reduced average levels of pollution, there was an almost complete disappearance of days with smoke levels exceeding 250 $\mu g/m^3$ and sulfur dioxide levels exceeding 500 $\mu g/m^3$ (0.18 ppm). As in earlier studies, some correlation remained between changes in the condition of the patients and daily concentrations of smoke and sulfur dioxide but the changes were small at these levels. At this low range of pollution, discrimination between the effects of pollution and those of adverse weather was poor.

Cohen et al. (1974) studied symptoms of irritation during a publicized and an unpublicized period of air pollution as well as during a control period in 3 communities in the New York metropolitan area during the summer of 1970. They used a telephone survey technique to inquire about specific symptoms such as eye irritation, throat irritation, chest discomfort, shortness of breath, restricted activity, and medical visits. No difference was noted between the 2 episodes of pollution. Both episodes showed significantly increased symptoms compared with the control period. The results indicated that irritative symptoms increased significantly when sulfur dioxide levels exceeded 310 $\mu g/m^3$ (0.11 ppm, West-Gaeke method) and total suspended particulates exceeded 145 $\mu g/m^3$ (high volume sampler) as a 3 day average. Sulfate levels ranged from 6.6 to 7.6 $\mu g/m^3$ in one area and 5.8 to 12.3 $\mu g/m^3$ in another area. In the second area, sulfate levels during the 2 periods of air pollution were 8.5 and 12.3 $\mu g/m^3$, respectively. Sulfate levels were not reported from the third area but were probably low. The authors drew attention to some of the problems associated with their study. The persons interviewed were generally wives and the symptomatology in the male population could have been underestimated. Also, there was an internal inconsistency possibly due to intercurrent infectious disease or socioeconomic differences. During the publicized episode, particulate pollution was considerably higher in the Bronx than in Queens whereas irritation symptoms were somewhat higher in Queens. The authors concluded that there could have been confounding effects of other air pollutants, intercurrent infection, or sociocultural factors.

Spirometric measurements were made at approximately weekly intervals on 18 patients with chronic obstructive lung disease for various periods during 1969-71 (Emerson, 1973). The spirometric values ($FEV_{1.0}$ and MEFR) were correlated with the levels of pollution (sulfur dioxide and smoke, British daily smoke/sulfur dioxide method) and climatic factors (temperature and humidity). Changes in $FEV_{1.0}$ in these patients were more strongly correlated with temperature and humidity than with concentrations of sulfur dioxide or smoke. Levels of air pollution in London were: sulfur dioxide, mean 190 $\mu g/m^3$ (0.07 ppm), maximum, 720 $\mu g/m^3$ (0.25 ppm) and smoke mean, 44 $\mu g/m^3$, maximum, 240 $\mu g/m^3$. One limitation of the study was that the pollution figures were averaged for 5-day periods, whilst the spirometric measurements were made on specific days.

Studies of patients with chronic bronchitis in Chicago, USA (Burrows et al., 1968; Carnow et al., 1969) showed conflicting results. The reasons for these differences are not clear but may be that different criteria for the selection of patients as well as different methods for the determination of the exposure of the individuals and their responses were used.

An unexpected finding of a possible effect of short-term exposure to

pollution arose from a study primarily concerned with long-term exposures. In a resurvey of adults in Vlaardingen (Netherlands) who had been interviewed and had lung function measurements made in 1969, Van der Lende et al. (1975) found that the average lung function values were higher in 1972 than in 1969, even though the subjects were 3 years older. When the authors examined the concentrations of pollution on the 2 occasions (each survey having been done within a 5-day period), they found that levels were relatively high in 1969 with daily values ranging from 15 to 140 $\mu g/m^3$ for smoke and from 120 to 300 $\mu g/m^3$ (0.04-0.11 ppm) for sulfur dioxide compared with values ranging from 15 to 40 $\mu g/m^3$ and 45-100 $\mu g/m^3$ (0.02-0.04 ppm), respectively, in 1972. The increase in lung function was most pronounced on the days with the greatest difference in the levels of pollution. A control population in a rural area showed no comparable changes over the same period, and temperature differences did not explain the effect.

Asthmatic subjects have also been studied. These patients represent a heterogeneous group and this may account for the variable responses that have been reported. Cohen et al. (1972) studied 20 asthmatic subjects living in a small town (Cumberland, WV, USA) in the vicinity of a coal-fired power plant. They found that when the soiling index exceeded 1.0 Coh unit, or sulfur dioxide concentrations (West-Gaeke method) exceeded 200 $\mu g/m^3$ (0.07 ppm), or total suspended particulates exceeded 150 $\mu g/m^3$ (high volume sampling method), or the temperature was lower than $0^{\circ}C$, there was a significant increase in the frequency of asthmatic attacks. Levels of sulfates exceeding 20 $\mu g/m^3$ and nitrate levels exceeding 2 $\mu g/m^3$ did not result in such an effect. In general, the effect of temperature was stronger than that of the air pollutants although each of the 5 air pollutants measured including sulfates and nitrates showed a correlation. When temperature and any one of the pollutants were controlled for in the analysis, the effect of any of the other 4 pollutants was eliminated. Temperatures below $0^{\circ}C$ overwhelmed any effect of the pollutants and higher levels of the pollutants reduced the effect of temperature. One further feature of this study should be stressed. Pollution in Cumberland was dominated by emissions from a large single source, and this might have led to high transient exposures to the pollutants, which included oxides of nitrogen as well as sulfur oxides and suspended particulate matter. In these circumstances it is doubtful whether the 24-h values provided an adequate index of exposure of the population.

Several studies on asthmatic subjects in Yokkaichi, Japan, have been reported by Yoshida et al. (1966) including one on a group of 13 patients in which the number of attacks increased from 1 to 4 per week when the concentration of sulfur dioxide was in the range of 140-230 $\mu g/m^3$ (0.05-0.08 ppm), rising to about 12 per week when the sulfur dioxide level reached

740 μg/m³ (0.26 ppm), all expressed as weekly means. Suspended particulate or smoke levels were not reported.

8.3.4 Morbidity in adults – effects of long-term exposures

Random samples of populations can be used for international comparisons where there are gradations of air pollution. The major difficulty here has been to ensure comparability with respect to occupational exposures and ethnic groups. Reid et al. (1964) reported such a comparison based on a study in the United Kingdom (College of General Practitioners' Study, 1961) and a survey in Berlin, NH, USA (Ferris & Anderson, 1962). The same questionnaire was used in both studies. In the United Kingdom, it was completed by a large number of practitioners who made up the survey group. In the USA, it was completed by 2 physicians who tried to maintain the criteria developed in the British survey. Results were standardized for cigarette smoking. The effects of air pollution were then examined by age group and sex. When simple bronchitis was present, i.e., phlegm production for 3 months out of the year for 2-3 years, standardizing for cigarette smoking removed any effect of air pollution for both males and females. A more severe form of chronic bronchitis characterized by phlegm production, exacerbations of colds that went to the chest, and shortness of breath when walking on the level at one's own pace – did show an association with air pollution for both males and females, even after standardizing for cigarette smoking. Levels of air pollution were measured in Berlin, NH, by the lead peroxide candle, dustfall, and high-volume samplers. Data for the United Kingdom were estimated from similar measurements obtained in comparable towns and cities where the general practitioners collected the data. In Berlin, NH, the sulfation rate (lead candle) was 730 μg SO_3/100cm² per day; in the United Kingdom, in the large towns it was 950 and in the large conurbations 1650 μg SO_3/100cm² per day. The results of this study seem to be consistent with those of other studies but it is not known whether differences in socioeconomic or ethnic status could have been relevant factors. The population of Berlin, NH, was resurveyed in 1967, and the results were compared with those obtained in 1961 (Ferris et al., 1973). There had been some decrease in pollution levels in the interval, the sulfation rate being 470 μg SO_3/100 cm² per day in 1967, compared with the earlier figure of 730, while the concentration of total suspended particulates had fallen from 180 to 132 μg/m³ (high-volume samples). Small reductions in the prevalence of respiratory disease were noted after standardizing for age and cigarette smoking. Slight improvements in forced vital capacity (FVC) and peak expiratory flow rate (PEFR) were also noted, but there was little change in $FEV_{1.0}$. There is some doubt about the relevance of the 180 μg/m³ figure quoted for total suspended particulates in the 1961 study, since it

referred only to a 2-month period at a single site. A random population sample from Chilliwack, BC, Canada, an unpolluted community, was studied by Ferris & Anderson (1964) and the results were compared with the results of the 1961 study in Berlin, NH. Respiratory symptoms, after standardization for age and cigarette smoking, tended to be higher in Berlin than in Chilliwack. Pulmonary function ($FEV_{1.0}$ and PEFR) was lower in Berlin than in Chilliwack, after standardization for age, height, sex, and smoking category. Pollution levels in Chilliwack (based on lead-candle measurements) were about one-tenth to one-sixth of those in Berlin, NH.

A third survey in this series was carried out in 1973 (Ferris et al., 1976). By this time, there had been a further decline in pollution by particulate matter, the annual mean concentration of total suspended particulates (high volume sampler) being quoted as 80 $\mu g/m^3$. Only limited data on sulfur dioxide were available; the mean of a series of 8-h samples for selected weeks was quoted as 0.01 ppm (30 $\mu g/m^3$). On this occasion, the authors did not find any appreciable differences in the prevalence of respiratory symptoms or in measures of lung function, as compared with the 1973 report. The interpretation of these findings is difficult, for the studies were concerned largely with consecutive investigations of survivors of the original group, over a 12-year period. Although the authors took into account, as far as possible, the effect of selective losses of some of the population, and changes in smoking habits among those who remained, there is still some doubt as to whether the three sets of results are truly comparable. The authors themselves concluded that either the changes in air pollution levels from 1967 to 1973 (which included a decline in total suspended particulates from about 130 to 80 $\mu g/m^3$ (annual mean) with possibly a slight increase rather than decrease in sulfur dioxide) were not associated with a beneficial effect on health, or that their methods were not sufficiently sensitive at the levels involved.

One of the difficulties in interpreting these data is that exposure to odorous air pollutants (Berlin, NH) also occurred, indicating an unconventional type of air pollution. It does seem reasonable, however, to interpret the results of these surveys as showing that slight changes in respiratory symptoms and pulmonary function were related to levels of pollution. Sulfur oxides and particulate matter may have been of importance. Only sulfation data are available for sulfur oxides in the 1961 study.

Extensive studies have been made of post office and telephone workers in the United Kingdom and USA (Holland & Reid, 1965; Holland & Stone, 1965; Holland et al., 1965). The authors carefully considered most of the relevant epidemiological variables and showed a gradation of symptoms across the levels of pollution, particularly in the 50 to 59-year-old category. However, since pollution was measured in different ways in each part of the studies, it is difficult to deduce any quantitative relationships with sulfur dioxide and

particulate matter. The differences in the prevalence of symptoms persisted when the authors examined the various smoking categories. They converted the small amount of pipe and cigar smoking to cigarette equivalents, which is not advisable, since other studies have indicated that pipe and cigar smoking are less markedly associated with respiratory symptoms. Lower levels of $FEV_{1.0}$ and PEFR were observed in the areas of higher pollution. The authors indicated that a difference in height of 2-4 cm between the two populations studied could not account for the differences seen in pulmonary function. Presumably, these pulmonary function values had been corrected for standard temperature and saturated vapour pressure. If not, some of the differences between values in the USA and United Kingdom could be explained by the fact that lower temperatures in England could have resulted in lower measured air volumes. Similar spirometers were used in both studies.

In another study in the United Kingdom, Lambert & Reid (1970) questioned about 10 000 adults by post. They estimated that their sample represented about 74% of those able to reply. The positive responses from the questionnaire (which had been recommended by the British Medical Research Council) were correlated with levels of pollution estimated from data used earlier by Douglas & Waller (1966) and from some data from the National Air Pollution Survey. The responses were controlled for social class and cigarette smoking. The authors reported that whereas nonsmokers showed little response to the levels of air pollution, cigarette smokers did respond and appeared to be more sensitive. They also noted a considerable rural/urban gradient, more pronounced in men than in women, that could not be explained by differences in smoking habits.

Extensive studies were carried out in the Ruhr area of the Federal Republic of Germany (Reichel et al., 1970; Ulmer et al., 1970) based on a short questionnaire on respiratory symptoms, physical examinations, and measurements of airways resistance using a body plethysmograph. There were no clear differences in the results between areas with different levels of pollution, but because of selection factors and a low response rate, no definite conclusions can be drawn from these studies regarding relationships with sulfur dioxide and particulate matter.

A study in Vlaardingen in the Netherlands by Van der Lende (1969) indicated that increased cough and phlegm production were associated with air pollution but decreased lung function was not. However, the author considered that the study might have been affected by the presence of allergens, such as spores and bacteria in the agricultural regions. Comparisons were made between an industrial area, polluted by sulfur dioxide and particulate matter, and an agricultural area with little pollution. In a later report, Van der Lende et al. (1973) indicated that the effect of pollution could have been masked by "self-selection" of the populations concerned.

The relationship between chronic bronchitis and air pollution was studied

in Osaka Prefecture, Japan, by Tsunetoshi et al. (1971). Surveys were made of all persons over 40 years of age in selected areas using self-administered questionnaires similar to that recommended by the British Medical Research Council. The authors' definition of chronic bronchitis was cough with sputum for 3 or more months, for at least 2 successive years. Pulmonary function was measured by the Vitalor, using the maximum value. An equation was developed relating prevalence of bronchitis to age, smoking, and sulfation rate (lead candle). The prevalence of bronchitis in the study areas ranged from about 4% (in males aged 40-59 years) in areas where the sulfation rate was close to 1 mg/100 cm^2 per day to about 10% in those around 3 mg/100 cm^2 per day. No data were given concerning the levels of particulate matter.

Many other studies on the prevalence of respiratory symptoms in relation to air pollution have been carried out in Japan such as that by Toyama et al. (1966). They reported prevalences ranging from 2.8 to 3.7% (males aged 40-59 years, adjusted for age and smoking to accord with other Japanese studies) in areas of Kashima (a nonindustrialized rural town, at that time) with sulfur dioxide concentrations of less than 30 $\mu g/m^3$ (0.01 ppm, automatic conductimetric method) and suspended particulate concentrations (high-volume sample) of 106-341 $\mu g/m^3$ (mean 197). An extensive survey in Tokyo, (Suzuki & Hitosugi, 1970, unpublished data)[a] showed a higher prevalence of chronic bronchitis in areas that were more polluted, ranging from 5.5% (males aged 40-59 years) and 1.1% (females 40-59 years) where the sulfur dioxide concentration was below 60 $\mu g/m^3$ (0.02 ppm, automatic conductimetric method), and the suspended particulate level was below 100 $\mu g/m^3$ (light-scattering method), to 6.7% (males) and 3.9% (females), where sulfur dioxide was over 140 $\mu g/m^3$ (0.05 ppm) and suspended particulates more than 200 $\mu g/m^3$. There was also some increase in prevalence in an intermediate area with sulfur dioxide concentrations of 60-140 $\mu g/m^3$ (0.02-0.05 ppm) and a suspended particulate concentration of 100-200 $\mu g/m^3$. Smoking habits were standardized in this study. In a recent study by Tani (1975) in the vicinity of a pulp mill at Fuji City, and in control areas, there appeared to be a consistent relationship between the prevalence of bronchitis and sulfation rates, as measured by lead candles, with a prevalence of about 3% (males and females combined, aged 40-59 years) in areas where the sulfation rate was around 0.6 mg/100 cm^2 per day to about 8% where it was 1.2 mg/100 cm^2 per day.

In studies on a random sample of adults in Cracow, Poland, the levels of

[a] Suzuki, T. & Hitosugi, M. Prevalence study of pulmonary symptoms in Tokyo Prefecture employees. A paper presented at a meeting of a Working Group on Air Pollution and Health, USA-Japan Cooperative Science Programme, East-West Center, Honolulu, 21-23 April, 1970. The pollution levels quoted in this study were obtained from reports of the Tokyo Metropolitan Government concerning air pollution levels for the years 1966-69 (Department of Environmental Pollution Control Tokyo, 1976).

pollution measured made it possible to classify the subjects into high and low exposure groups (Sawicki, 1972). The levels in the high pollution area were an annual mean smoke level of 170 $\mu g/m^3$ and an annual mean sulfur dioxide level of 125 $\mu g/m^3$ (0.04 ppm). In the low pollution area, the standard smoke annual mean was 90 $\mu g/m^3$ and the sulfur dioxide annual mean was 45 $\mu g/m^3$ (0.02 ppm). Persons residing in the more polluted area had more respiratory symptoms and poorer pulmonary function than those residing in the area with lower pollution (chronic bronchitis 19% in more polluted area and 11% in less polluted area and asthmatic disease 11% in more polluted area and 5% in less polluted area). Sawicki considered that there was a synergistic interaction with cigarette smoking. He also pointed out that many of the inhabitants worked outside the area in which they lived and, therefore, the exposure levels at their places of residence might not represent their true exposures.

8.3.5 Morbidity in children

Studies of the health of children have also provided useful information.

Douglas & Waller (1966) performed a cohort study based on a national sample of children born in the United Kingdom in the first week of March 1946. The children were followed medically for 15 years by health visitors and school doctors. The study was restricted to the 3131 children who remained at the same address for the first 11 years of the enquiry, or who moved to an area that was in a similar pollution group. Levels of air pollution were estimated from the amount of coal consumed in a given area where each child lived, and it was shown at the end of the study that the 4 pollution categories that had been defined provided a satisfactory gradation in terms of the measurements of smoke and sulfur dioxide that were then available. In each of the several periods of life considered, from birth onwards, the authors noted a consistent relationship between the frequency of lower respiratory tract infections and pollution category. There was no sharp change at any particular pollution level, but if the rates within the lowest category (mainly rural areas) were taken as a baseline, then increased frequencies were seen in the next category up, with smoke and sulfur dioxide each of the order of 140 $\mu g/m^3$ (0.05 ppm sulfur dioxide) or more. Annual means were estimates based on the British daily smoke/sulfur dioxide method for a period after the end of the study and probably underestimated earlier level. Socioeconomic status was important in the study, but a relationship between air pollution and frequency of lower respiratory tract infections still existed within separate social classes. In a later follow-up of these subjects, Colley et al. (1973) showed that, at the age of 20 years, respiratory symptoms were related to smoking habits rather than to the pollution of the areas in which the subjects were then living. However, there was some relationship between

the prevalence of symptoms and earlier histories of lower respiratory tract infections, which, in turn, were related to estimated pollution exposures during childhood.

Lunn et al. (1967) studied 819 children in their first year at school in the industrial city of Sheffield, in the United Kingdom. Medical examinations were carried out on the children, the parents were questioned concerning the previous health of the children, and $FEV_{0.75}$ and FVC were measured. Various socioeconomic factors were also carefully considered. The families were stable, and there had been little or no migration into or out of the specific communities. Measurements of pollution were made at the schools attended by the children (British daily smoke/sulfur dioxide method). The authors found increased frequencies of both upper and lower respiratory tract infections in the more polluted areas. When the "cleanest" area was taken as the baseline, most of the illness indices considered showed an increase in the next area up in order of pollution levels, i.e., where the annual mean concentrations of smoke and sulfur dioxide were each about 200 $\mu g/m^3$ (0.07 ppm sulfur dioxide) taking figures for the middle year of the survey. A follow-up study was carried out on some of these children when they were 4 years older (i.e., aged 9) (Lunn et al., 1970). By then, the implementation of the Clean Air Act had reduced the contrast in pollution between the areas, so that the mean concentration of smoke in the 3 "dirty" areas combined was about 140 $\mu g/m^3$ and the mean sulfur dioxide concentration was 200 $\mu g/m^3$ (0.07 ppm), compared with about 50 and 100 $\mu g/m^3$ (0.04 ppm sulfur dioxide), respectively, in the "clean" area. At this time, there was no significant difference in the illnesses reported by the 9-year-olds in the different areas and the authors concluded that this was in line with the reduced pollution levels.

Data were collected (Holland et al., 1969) concerning about 11 000 children attending school in 4 areas of Kent, England, 2 of which were predominantly urban, and 2, rural. As part of the children's regular medical examinations, peak expiratory flow rates, height, weight, and the results of examinations of ears and tonsils were recorded. Smoking habits and school absences were also recorded. Questionnaires concerning such factors as previous respiratory diseases, father's occupation, and size of family were completed by the parents. Smoke and sulfur dioxide were measured in 3 of the areas (British daily smoke/sulfur dioxide method) and information on population density and housing was collected. Four factors emerged as important in relation to decreased peak expiratory flow rates. Place of residence was most important followed by previous history of respiratory disease; family size and social class were of least importance. These 4 factors seemed to be additive but they only accounted for 10-15% of the total variation. Levels of air pollution for smoke were reported to range from

34 to 69 μg/m³ in the 3 communities. Values for sulfur dioxide were not reported but were stated to parallel those for smoke. There were clearly other factors affecting area difference, and there is some doubt as to whether the small contrasts in pollution could have had much effect.

Colley & Reid (1970) surveyed about 11 000 children from 6 to 10 years of age, living in urban and rural areas of England and Wales. The prevalence of respiratory disease was assessed in the autumn. Pollution was assessed in terms of sulfur dioxide concentration, from some direct measurements (British daily smoke/sulfur dioxide method) coupled with estimates based on lead candle measurements of sulfation. Within the English areas studied (winter mean concentrations of sulfur dioxide ranging from about 30 to 150 μg/m³ or 0.01-0.05 ppm) there was a gradient in the prevalence of symptoms, but the rates were much higher in Wales for comparable levels of pollution. The reasons for this difference were not clear, although it has been suggested that it could be related to the fact that solid-fuel consumption was high in Wales.

Respiratory function measurements were made on children aged 10 -11 years from 2 different areas of the German Democratic Republic (Berlin and Bitterfeld) with different levels of pollution (Grosser et al., 1971). The groups were matched for social class, age, and height. In the low pollution area, the concentration of respirable dust (method not mentioned) was 110 μg/m³ and that of sulfur dioxide (method not mentioned) was 50 μg/m³ (0.02 ppm); in the other area, the figures were 290 and 360 μg/m³ (0.13 ppm), respectively (based on 24-h measurements, averaged for July and December). Two studies were made, 6 months apart, in each of the 2 areas. Each of the spirometric values studied (FVC, $FEV_{1.0}$, $FEV_{0.75}$) was higher in the area with lower pollution.

A variety of other techniques has been used to investigate possible effects of exposure to pollution. These include the work of Yoshii et al. (1969) who noted an association between chronic pharyngitis accompanied by histopathological changes at biopsy and level of sulfation, expressed as the annual mean, in persons attending their clinic in Yokkaichi, Japan, and in sixth-grade children. In the heavily polluted districts sulfation rate was more than 1.0 mg/100 cm² per day, in moderately polluted districts it ranged from 0.25 to 1.0 mg/100 cm² per day, and in the control area it was less than this level (lead candle measurements).

Conjunctivitis, both acute and chronic, has been reported in Zabrze, Poland, in relation to industrial air pollution (Maziarka & Moroz, 1968). In Czechoslovakia, Schmidt et al. (1966) reported differences in the blood cells, tonsils, and cervical lymph nodes of children living in a highly polluted atmosphere compared with those living in a relatively clean atmosphere and Symon et al. (1969) reported retardation in growth and ossification and a reduced colour index in red blood cells in children living in areas with high air levels of sulfur

dioxide (up to 2-3 mg/m^3) and fly ash. None of these studies can be used for the exposure-effect relationship.

8.3.6 CHESS studies

The US Environmental Protection Agency has recognized the need for studies at relatively low levels of air pollution in order to determine whether a no-effect level can be identified to develop a dose-response relationship and to monitor areas where there might be a change in the levels of exposure. The CHESS (Community Health and Environmental Surveillance System) studies were developed with these purposes in mind. In some aspects these studies have been well designed and executed but in other aspects there have been difficulties. In many ways these are preliminary studies that need to be continued. The studies have included adults, children, asthmatic subjects, and patients with cardiovascular and pulmonary diseases. Both acute and chronic effects have been studied. Methods have involved mailed questionnaires on respiratory symptoms and illnesses (adults and children), mailed questionnaires on family composition, housing, and socioeconomic status, telephone interviews, tests of pulmonary function (children), and diary techniques with patients.

Previous exposures to air pollutants were estimated from historical data on emissions or known production figures from the local industries and the application of mathematical models. More recent exposures were based on actual measurements. These were generally conducted at monitoring stations (each of which covered a radius of up to 2 km), and involved high volume sampling for total suspended particulates and suspended sulfates, and the West-Gaeke method for sulfur dioxide. Mathematical models were used to estimate the variation in exposure of the different groups. Various problems discussed in a summary of the results (US Environmental Protection Agency, 1974) include poor response rates (i.e., low participation rates) in some of the studies on children, high dropout rates in studies on patients, and, in at least one of the studies on children, the fact that their spirometry was probably in error.

There was a general tendency for the authors to over-interpret the CHESS data. In some of the studies on children, the results were grouped according to high and low levels of pollution and a difference was found between the two groups. However, the relationship of the prevalence of disease to levels of pollution was not clear – namely, when the individual groups were examined, some exposed to the high levels of pollution had a lower disease prevalence than some of the groups exposed to low levels of pollution.

The design for the study of the impact on respiratory disease was excellent and took into account family composition, housing, and socioeconomic status. It is unfortunate that these studies were not continued for more than

one year of observation before reporting. A number of years of observations are needed to rule out natural fluctuations in respiratory disease.

These studies have been reviewed by an expert committee in the USA under the chairmanship of Dr D. Rall (Director, National Institute of Environmental Health Sciences, US Department of Health, Education and Welfare) (Rall, 1974). The Committee's evaluation of the studies was similar to that of the Task Group and the Committee concluded that the results of the studies did not warrant any change in the present US Federal Air Quality standards.

It was the opinion of the WHO Task Group that these data could not be used for the estimation of an exposure-effect relationship.

8.3.7 Lung cancer and air pollution

The possibility that air pollution is a causal factor in cancer of the lung has given rise to considerable concern. The evidence in favour of a causal relationship is briefly: (*a*) the excess occurrence of the disease in urban areas; (*b*) the presence in the suspended matter in urban air of substances such as benzo(a)pyrene that can cause cancer under experimental conditions; and (*c*) the general rise in lung cancer that appeared, at one time, to follow certain assumed trends in pollution.

Early studies in the United Kingdom (Stocks, 1959, 1966) indicated that variations in lung cancer mortality in urban areas were associated with variations in amounts of pollution and, following a recommendation by a WHO Study Group in 1959 (World Health Organization, 1960), a pilot international study was undertaken in several cities where there were contrasts in lung cancer death rates. The results did not show any clear-cut relationship with measurements of particulate matter or its benzo(a)pyrene content (Waller & Commins, 1967) and it was clear that apart from the difficulties of making proper allowances for differences in smoking habits, it seemed likely that present-day measurements of polycyclic hydrocarbons gave an inadequate assessment of past exposures to these compounds.

The Royal College of Physicians of London (1970) reviewed the issue, and concluded that the evidence against community air pollution being a causal factor in lung cancer was stronger than the evidence for it. The urban/rural differential is greatest in countries with relatively low urban air pollution (Sweden, Norway, Denmark). The upward trend in mortality as well as other experimental and epidemiological evidence are best explained by the causal role of cigarette smoking.

Nevertheless, in a review by Cleary (1967), evidence is presented to show that, in Australia, New Zealand, South Africa, and the USA, immigrants from the United Kingdom have a higher lung cancer death rate than those born in these countries: immigrants from Norway have a lower rate than native-born citizens of the USA, and the lung cancer mortality rates for all these migrants

are intermediate between those of their countries of origin and destination, strongly suggesting an environmental factor in early life.

While the existence of an urban excess of lung cancer has been proved, it is uncertain that air pollution is the "urban factor" responsible. In contrast, recent work incriminates cigarette smoking more strongly than ever; there is also a contribution from some specific occupational exposures (see footnote in section 1.1.7).

The consideration of criteria for environmental carcinogenesis specifically in relation to any possible effects on lung cancer, is outside the scope of the present discussion, but it may be mentioned that any action to reduce smoke and especially that from the inefficient combustion of coal in domestic fires, is likely to make substantial reductions in the benzo(a)pyrene content of the air. Such a change has already been noted in London, where the concentration of this compound is now only about one-tenth of what it was 25 years ago (Lawther & Waller, 1976). A reduction of sulfur dioxide may also be important for any possible interactions relating to the production of lung cancer. Some experimental studies (Kuschner & Laskin, 1971; Skvorcova et al., 1973) showed an increased carcinogenic response when laboratory animals (rats and hamsters) were exposed to sulfur dioxide in addition to benzo(a)pyrene.

8.3.8 Annoyance

Annoyance may be defined as "a feeling of displeasure associated with any agent or condition believed to affect adversely an individual or a group". This definition was adopted by an international symposium on annoyance in Stockholm in 1971 (Lindvall & Radford, 1973). Very few studies have been performed that would make quantitative evaluations of this effect possible.

The social awareness of pollution caused by particulate matter has been studied in a few areas. The results from different studies have been presented in a document on particulate matter (US Department of Health, Education and Welfare, 1969a); they include those from a study carried out in St. Louis (Schusky, 1966), where values for suspended particulates of around 100 $\mu g/m^3$ produced annoyance reactions from a considerable number of people.

A similar study was carried out in Birmingham, Alabama, USA (Stalker & Robinson, 1967), in which levels of air pollution were correlated with annoyance. They found that, as dustfall reached or exceeded 14.1 g/m^2 per month, about one-half of the population considered it to be a nuisance; at 10.5 g/m^2 per month, about one-third of the population considered air pollution a nuisance. Stepwise multiple regression analysis showed that the variation due to dust fall alone explained 49% during the spring season and 68% during the winter season of the total association between the air

pollutants measured and public annoyance. The association between levels of suspended particulate matter and public opinion, which was weaker than that of dustfall, was strongest during the summer season (r=0.59). About one-half of the persons interviewed thought that air pollution was a general nuisance, when mean annual or mean summer concentrations of particulate matter reached 230 $\mu g/m^3$ and one-third, when they reached 150 $\mu g/m^3$.

No such relationship was shown with sulfur dioxide concentrations. However, these levels were low. Further studies are indicated, since it may be that effects such as annoyance reactions will, in the future, be the critical effects on which criteria, as regards the protection of public health, will be based. Since annoyance reactions have a large sociocultural component, these levels may vary from place to place and should be determined for each locality. Surveys on annoyance are fraught with many problems. When proper survey techniques are expertly applied, however, it will be possible to assess reactions in a quantitative manner.

Table 15. Exposure-effect relationships of sulfur dioxide, smoke, and total suspended particulates: effects of short-term exposures

concentration 24-h mean values ($\mu g/m^3$)			
Sulfur dioxide	Smoke	Total suspended particulates	Effects
>1000	>1000	–	London, 1952. Very large increase in mortality to about 3 times normal, during 5-day fog. Pollution figures represent means for whole area: maximum (central site) sulfur dioxide 3700 $\mu g/m^3$, smoke 4500 $\mu g/m^3$ (Ministry of Health, UK, (1954).
710	750	–	London, 1958-59. Increases in daily mortality up to about 1.25 times expected value (Lawther, 1963; Martin & Bradley, 1960).
500	500	–	London, 1958-60. Increases in daily mortality (as above) and increases in hospital admissions, becoming evident when pollution levels shown were exceeded (magnitude increasing steadily with pollution) (Martin, 1964).
500	–	–	New York 1962-66. Mortality correlated with pollution: 2% excess at level shown (Buechley, 1973).
500	250	–	London, 1954-68. Increases in illness score by diary technique among bronchitic patients seen above pollution levels shown (means for whole area) (Lawther et al., 1970).
300	140	–	Vlaardingen, Netherlands, 1969-72. Temporary decrease in ventilatory function (Van der Lende et al., 1975).
200 [a]	–	150 [b]	Cumberland, WV, USA. Increased asthma attack rate among small group of patients, when pollution levels shown were exceeded (Cohen et al., 1972).

[a] West-Gaeke method

[b] High volume sampling method

Other measurements by Organization for Economic Cooperation and Development or British daily smoke/sulfur dioxide methods (Ministry of Technology, UK, 1966; Organization for Economic Cooperation and Development, 1965).

8.4 Exposure-Effect Relationships

Some of the studies reported in this section can be used to develop exposure-effect relationships. It has been necessary to develop 2 tables, one for the effects of short-term exposures (Table 15, p. 85) and another for the effects of long-term exposures (Table 16). The results from the studies have been based on different methods of measuring sulfur oxides and

Table 16. Exposure-effect relationships of sulfur dioxide, smoke, and total suspended particulates: effects of long-term exposures

Concentration Annual means of 24-h mean values (μg/m³)			
Sulfur dioxide	Smoke	Total suspended particulates	Effects
200	200	–	Sheffield, England. Increased respiratory illnesses in children (Lunn et al., 1967, 1970)
–	–	180 [b]	Berlin, NH, USA. Increased respiratory symptoms, decreased respiratory function in adults (Ferris et al., 1973)
150	–	–	England & Wales. Increased respiratory symptoms in children (Colley & Reid, 1970)
125	170	–	Cracow, Poland. Increased respiratory symptoms in adults (Sawicki, 1972)
140 [d]	140 [d]	–	Great Britain. Increased lower respiratory tract illnesses in children (Douglas & Waller, 1966)
60-140 [a]	–	100-200 [c]	Tokyo, Increased respiratory symptoms in adults (Suzuki & Hitosugi, unpublished data, 1970)

[a] Automatic conductimetric method

[b] High volume sampler (2-month mean, possible underestimation of annual mean).

[c] Light-scattering method, results not directly comparable with others.

[d] Estimates based on observations after end of study; probable underestimation of exposures in early years of study.

Other measurements by Organization for Economic Cooperation and Development or British daily smoke/sulfur dioxide methods (Ministry of Technology, UK, 1966; Organization for Economic Cooperation and Development, 1965).

particulate matter. The values for the sulfur oxides are treated as if they were comparable. For the particulate matter, two categories are listed: smoke as measured by the Organization for Economic Cooperation and Development or British daily smoke/sulfur oxide methods and total suspended particulates as measured by the high volume sampler or light scattering. These factors should be considered in interpreting these tables.

9. EVALUATION OF HEALTH RISKS FROM EXPOSURE TO SULFUR OXIDES, SMOKE, AND SUSPENDED PARTICULATE MATTER

It is well established that respiratory diseases are important causes of disability and death, and that, for some of them, there is evidence of association with environmental factors in the ambient air. There is evidence that exposure

to mixtures of urban air pollutants containing sulfur oxides and particulate matter is related to a variety of adverse effects on health, even when other factors are controlled (section 8 – Tables 15 and 16). Although in most of the studies considered the levels of air pollution have been expressed in terms of sulfur dioxide, smoke, or suspended particulate matter, this does not necessarily imply that these are the causative agents. They provide only indices of pollution, and certain components, such as sulfuric acid or sulfates, may be of particular importance. Measurements of some of these components have now been made in a number of areas and used in some of the more recent epidemiological studies. The Task Group concluded, however, that, at present, there are not enough data on any of these other indices of pollution to allow exposure-response relationships to be established. Thus, the present discussion is confined to the effects of pollution expressed in terms of sulfur dioxide, smoke, and total suspended particulate matter.

9.1 Exposure Levels

Concentrations of sulfur dioxide, smoke, and suspended particulate matter vary greatly from place to place and from time to time. Many factors including sources, topography, and weather conditions may be involved in these variations.

An annual arithmetic mean of sulfur dioxide concentrations in urban areas typically ranges from 100-200 $\mu g/m^3$ (0.035-0.070 ppm), whereas a maximum daily mean ranges from 300-900 $\mu g/m^3$ (0.11-0.32 ppm). For smoke, an annual arithmetic mean ranges from 30-200 $\mu g/m^3$ with a maximum daily mean of 150-900 $\mu g/m^3$; for total suspended particulates, these levels range from 60-500 $\mu g/m^3$ and 150-1000 $\mu g/m^3$, respectively.

Comparatively little information is available concerning indoor concentrations of sulfur dioxide and particulate matter, though, in general, these levels are known to be lower than those outdoors, except at work places.

Levels in working environments are considerably higher than general community levels and are thought to have been much higher in the past.

In evaluating exposure levels that have been used in the past in connexion with epidemiological studies, a serious question arises as to how far these measurements, often intended primarily for control or monitoring purposes, can be considered as providing adequate measures of exposure. As discussed in section 5, it must be recognized that all the figures quoted in subsequent sections are based on measurements that have been made outdoors, usually at only a limited and not wholly representative set of fixed sites, though most people spend much time indoors, where concentrations may differ substantially from those outside. However, this does not necessarily invalidate these data which are serving primarily as indices.

So far, there has been little information on the particle size distribution and the chemical composition of selected particle size ranges that would make the nature of exposure more understandable.

Comparable assessment is often difficult because of differences in the methods of measurement of particulate matter that have been used in the health effect studies. Smoke, assessed in terms of blackness, is a measure of pollution associated with the incomplete combustion of fuel, and total suspended particulates, determined by weight, is a wider concept that includes all material which, by virtue of its particle size, remains in suspension for long periods.

9.2 Experimental Animal Studies

Laboratory studies have been performed using a variety of test animals, of periods of exposure, of experimental designs in exposure, and of combinations of pollutants and other agents.

Some of these studies have provided useful information on the mechanisms of the biological action of sulfur dioxide, sulfuric acid mist, or particulate matter. However, the results are of limited value in developing guidelines for the protection of human health from effects of these pollutants as they exist in urban areas, and for this reason it is necessary to turn to the available epidemiological evidence.

9.3 Controlled Studies in Man

Effects studied in volunteers under controlled conditions include those on the functions of the respiratory system, sensory organs, and cerebral cortex. Durations of exposure have been very short, usually less than a few hours.

Slight effects on pulmonary function were observed with exposure to sulfur dioxide at a concentration of 2100 $\mu g/m^3$ (0.75 ppm), but not with exposure to a concentration of 1100 $\mu g/m^3$ (0.37 ppm).

With exposure to sulfuric acid, a decrease in tidal volume was found at a concentration as low as 350 $\mu g/m^3$.

Combined exposures to sulfur dioxide and ozone or hydrogen peroxide produced a greater effect on respiratory function than exposure to each compound alone.

Studies on sensory and cerebral cortical functions showed that sulfuric acid was more toxic than sulfur dioxide and that a combination of these two substances produced an approximately additive effect.

There is a limit to the use of these studies for the development of criteria for community exposures, particularly when long-term exposure to complex mixtures of air pollutants is involved.

9.4 Effects of Industrial Exposures

Effects on the health of workers have been studied in relation to exposure to sulfur dioxide, particulate matter, or sulfuric acid mist arising from various manufacturing processes. In many of these studies, exposure levels were relatively high and, in some studies, adverse effects were detected only at a daily mean sulfur dioxide concentration as high as 70 000 $\mu g/m^3$ (25 ppm).

It has also been reported that exposure to sulfuric acid at a mean concentration of 1400 $\mu g/m^3$ during working hours for 2 days did not produce any effect on lung function.

The fact that adverse effects have not been reported at comparatively high levels of sulfur dioxide or sulfuric acid aerosols may well be explained by the influence of biasing factors, such as that the workers remaining in jobs with exposures to pollutants consist of people especially resistant to their effects. Therefore, it should not be considered an indication that such concentrations are without effects for the average working population and particularly not for workers with pre-existing pulmonary diseases.

In evaluating the effects from industrial exposures, due attention must also be given to the variation in chemical composition and size distribution of particulate matter.

9.5 Effects of Community Exposures

Many of the epidemiological studies in relation to community exposures that were considered by a WHO Expert Committee in 1972 (World Health Organization, 1972), and which must still be relied on to a large extent today, were based on the measurement of smoke rather than of total suspended particulates. However, some new data on the effects of total suspended particulates have become available and have been included in Tables 15 and 16 (section 8).

Tables 17 and 18 show the levels above which some effects on health might be expected among specified populations for short-term and long-term exposures, respectively. These are based on the critical evaluation of the results of studies reviewed in section 8.

In developing Table 17, greater emphasis had to be placed on some earlier results related to major effects seen when concentrations of pollution were much higher than those commonly experienced today. With the effective control of at least some components in areas where pollution was, at one time, very high, most of the more recent studies have failed to isolate the effects of the pollutants in question from effects similar in nature but arising from other factors.

The figures for sulfur dioxide and smoke are essentially the same as those

Table 17. Expected effects of air pollutants on health in selected segments of the population: effects of short-term exposures [a]

Expected effects	24-h mean concentration ($\mu g/m^3$)	
	Sulfur dioxide	Smoke
Excess mortality among the elderly or the chronically sick	500	500
Worsening of the condition of patients with existing respiratory disease	250	250

[a] Concentrations of sulfur dioxide and smoke as measured by OECD or British daily smoke/sulfur dioxide method (Ministry of Technology, UK, 1966; Organization for Economic Cooperation and Development, 1965). These values may have to be adjusted in terms of measurements made by other procedures.

proposed by the Expert Committee in 1972 (World Health Organization, 1972) the only change being the adoption of 250 $\mu g/m^3$ (0.09 ppm) instead of 250-500 $\mu g/m^3$ (0.09-0.18 ppm) as the level at which the worsening of the condition of patients from short-term exposures to sulfur dioxide might be expected. It was recognized that the magnitude of responses at this level appeared to be small and difficult to separate from effects due to other factors such as weather or infections. It is possible that a lower figure for smoke could now be adopted, but, in view of uncertainties concerning the differences in composition of this component of pollution from one area to another, and the changes with time even within one locality, it was felt that any further modification of the figure determined on the basis of the older studies from London would need new evidence.

Table 18 represents an overall assessment of the effects of long-term exposure to sulfur dioxide and smoke in terms of increases in the prevalence of respiratory symptoms among both adults and children, and in terms of the

Table 18. Expected effects of air pollutants on health in selected segments of the population: effects of long-term exposures [a]

Expected effects	Annual mean concentration ($\mu g/m^3$)	
	Sulfur dioxide	Smoke
Increased respiratory symptoms among samples of the general population (adults and children) and increased frequencies of respiratory illnesses among children	100	100

[a] Concentrations of sulfur dioxide and smoke as measured by OECD or British daily smoke/sulfur dioxide method (Ministry of Technology, UK, 1966; Organization for Economic Cooperation and Development, 1965). These values may have to be adjusted in terms of measurements made by other procedures.

increased frequency of acute respiratory illnesses, that has been demonstrated particularly among children.

For each pollutant there remains much uncertainty about the minimum levels associated with demonstrable effects. Where populations exposed to different levels of pollution have been compared, it cannot necessarily be

assumed that even those who were exposed to a level lower than the known lowest effect level are entirely unaffected by pollution. There must also be doubts as to whether the effects observed in some studies were due in part to other pollutants, or to socioeconomic or other factors that had not been adjusted for completely.

No firm conclusion was reached on the effects of total suspended particulates as a component of air pollution, together with sulfur dioxide, because of the limited amount of information available. For the effects of long-term exposure, a tentative figure of 150 $\mu g/m^3$ (annual arithmetic mean) was suggested, based on the 2 entries in Table 16, recognising that one of these was based on light-scattering observations, and the other on high volume sampler measurements, but for a 2-month period only. It was noted that the one study on the effects of short-term exposure to total suspended particulates had been included in Table 15, but it was felt that this could not provide satisfactory information for an assessment of these effects.

The figures in Table 18 have been expressed in terms of annual arithmetic mean concentrations, although it is not known whether the effects are related to extended exposures to these average levels, or more particularly to days of high pollution within each series. In view of the limited quantitative information on effects of pollution in terms of annoyance, this aspect has been omitted from Tables 17 and 18.

9.6 Guidelines for the Protection of Public Health

Tables 17 and 18 present two different sets of criteria, one relating to effects of short-term exposure, in terms of 24-h average concentrations, and the other to effects of long-term exposure in terms of annual means. These effects may be interrelated; the gradual development of respiratory symptoms may, for example, be a reaction to repeated short-term exposure to peak 24-h values, or even to transient peaks lasting for still shorter periods, but in the absence of any substantial evidence on this point, the two criteria must, for the time being, be considered separately.

With the present state of knowledge, it was considered that a safety factor of two below the figures given in Tables 17 and 18 would be reasonable to ensure the protection of public health, and, accordingly, Table 19 was developed, still considering the effects of short-term and long-term exposures separately. As an indication of the uncertainty surrounding these estimates, the figures have further been expressed with a range of ± 20%.

The values proposed in Table 19 are in general agreement with those suggested as long-term goals in the earlier report (World Health Organization, 1972). In the case of sulfur dioxide, there has been some reduction in the 24-h figure (if this is regarded as a level not to be exceeded on more than 7

days a year), and this is in line with the revision of the "effect" level from a range of 250 to 500 μg/m³ in the 1972 report, to the present figure of 250 μg/m³ (Table 17).

Table 19 requires careful interpretation, for none of the figures can be considered as absolute limits. In the first place, day-to-day variations in the concentration of smoke and sulfur dioxide are determined largely by weather conditions, and occasional peaks far beyond the usual daily values may well occur, even with careful control of emissions.

Table 19. Guidelines for exposure limits consistent with the protection of public health [a]

	Concentration (μg/m³)	
	Sulfur dioxide	Smoke
24-h mean	100-150	100-150
Annual arithmetic mean	40-60	40-60

[a] Values for sulfur dioxide and smoke as measured by OECD or British daily smoke/sulfur dioxide method (Ministry of Technology, UK, 1966; Organization for Economic Cooperation and Development, 1965). Adjustments may be necessary where measurements are made by other methods.

Although there are two sets of conditions specified in Table 19, determined independently from evidence on the effects of short- and long-term exposures, they can generally be considered to be consistent with one another. If the proportion of days with 24-h values above those in Table 19 is small (e.g., of the order of 7 days per year), then the annual means may well fall within or below the ranges specified in the second row of the table. Annual means are specified here in terms of arithmetic means: the corresponding geometric means would generally be a little lower (see section 5).

Much consideration was given to the possibility of extending Table 19 to include guidelines for total suspended particulates as measured by the high volume sampler but it was concluded that the available evidence on the effects associated with exposure to suspended particulate matter was highly unsatisfactory.

The Task Group felt, however, that some recommendations for a guideline should be made. A tentative annual mean value of 150 μg/m³ has been suggested in section 9.5 as a level beyond which effects of long-term exposure to total suspended particulates might be observed. Applying a safety factor of two and introducing a ± 20% range, as in the case of smoke and sulfur dioxide, would then provide a range of levels from 60 to 90 μg/m³ as a possible guideline.

For short-term exposures, no satisfactory, direct evidence relating concentrations of total suspended particulates to effects is available. Because of this, a guideline for short-term exposure levels can only be inferred. Assuming that the same ratio of 24-h mean concentrations to the annual mean (each

derived independently, see beginning of section) given in the guidelines for smoke, is applicable to suspended particulate matter, then a very approximate 24-h guideline for suspended particulate matter, as measured by the high volume sampler, would be in the order of 150 to 230 $\mu g/m^3$.

While the Group felt that it was reasonable and prudent to consider the above figures as interim guidelines consistent with the protection of public health, it stressed the very urgent need for additional information on the effects of exposure to suspended particulate matter (measured by the high-volume sampler). Furthermore, it recognized the fact that the toxicological significance of total suspended particulates might vary depending on their chemical composition and particle size, and that under certain circumstances, the suggested guidelines might need to be reconsidered. It should be noted that the discussion above does not imply any preference for smoke measurements over those of total suspended particulates; indeed it is highly desirable to develop more appropriate methods for the measurement of suspended particulates, especially those limited to the measurement of respirable particles.

It was recognized that in many urban and industrial areas existing levels of pollution by sulfur dioxide and suspended particulate matter were substantially above these guidelines. Furthermore, there was the problem that the long-distance transport of these pollutants from major sources could, in some circumstances, result in comparatively high background concentrations in rural areas, and high levels in the incoming air in towns striving to meet their own air quality standards. It was considered, however, that every effort should be made to develop control procedures that would allow these guidelines to be met.

These guidelines are based on observations among populations in the community exposed to a mixture of sulfur dioxide and smoke or total suspended particulates and they may not apply to situations where only one of the components is present. On grounds of prudence, however, it is recommended that the levels of each pollutant should be below the values stated. It should be stressed again, however, that the data on which the guidelines are based are uncertain and each of the guidelines is tentative and subject to review when further information becomes available.

It was the opinion of the Group that there is not yet sufficient information available on the effects of community exposures to sulfuric acid aerosols or suspended sulphates to develop guidelines for these air pollutants.

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