Chapter 7.4 Sulfur dioxide

General description

Historically, sulfur dioxide (SO_2) and particulate matter derived from the combustion of fossil fuels have been the main components of air pollution in many parts of the world. The most serious problems have been experienced in large urban areas where coal has been used for domestic heating purposes, or for poorly controlled combustion in industrial installations. In such situations the complex of pollutants has generally been considered collectively, drawing on findings from epidemiological studies done several decades ago in areas formerly heavily polluted. Guidelines developed in this way had been related to averaging times of 24 hours in respect of acute effects and one year in respect of chronic effects.

Separate attention has been given to sulfur dioxide alone, based largely on findings from controlled human exposure studies. These allow guidelines to be developed in terms of shorter averaging periods, of the order of one hour. These are relevant to exposures to peak concentrations that may arise from sources burning coal or heavy oil, whether or not accompanied by substantial concentrations of particulates. Epidemiological studies published in the last decade provide further evidence on the health effects of sulfur dioxide. Thus a section has been introduced in this revision focusing on epidemiological results in locations where the sources of pollution are mainly motor vehicles and various industries.

Sulfur dioxide is derived from the combustion of sulfur-containing fossil fuels and is a major air pollutant in many parts of the world. Oxidation of sulfur dioxide, especially at the surface of particles in the presence of metallic catalysts, leads to the formation of sulfurous and sulfuric acids. Neutralization, by ammonia, leads to the production of bisulfates and sulfates.

Sulfur dioxide is a colourless gas that is readily soluble in water. Sulfuric acid is a strong acid that is formed from the reaction of sulfur trioxide gas (SO_3) with water. Sulfuric acid is strongly hygroscopic. As a pure material it is a colourless liquid with a boiling point of 330 ^{o}C. Ammonium bisulfate (NH_4HSO_4), which is less acidic than sulfuric acid as a pure material, is a crystalline solid with a melting point of 147 ^{o}C. The formation of very small particles of sulfuric acid occurs by nucleation. Many vapours are able to condense on the surface of existing very fine nuclei and lead to the growth of composite particles. Sulfuric acid vapour, unlike many other vapours, exhibits the property of being able to condense and produce nuclei *de novo*.

Sources

Natural sources, such as volcanoes, contribute to environmental levels of sulfur dioxide. In the European Region, man-made contributions are of the greatest concern. These include the use of sulfur-containing fossil fuels for domestic heating and for power generation. In recent years the use of high-sulfur coal for domestic heating has declined in many western European countries, and power generation is now the predominant source. This has led to a continued reduction in levels of sulfur dioxide in cities such as London, which were once heavily polluted. The use of tall chimneys at power stations has led to widespread dispersion and dilution of sulfur dioxide. These changes in pattern of usage have led to urban and rural

concentrations becoming similar; indeed in some areas rural concentrations now exceed those in urban areas.

Occurrence in air

As a result of changes in sources, annual mean levels of sulfur dioxide in the major cities of Europe have fallen since the previous edition of *Air quality guidelines for Europe (1)* and are now largely below 100 μg/m^3. Daily mean concentrations have also fallen and now are generally below 500 μg/m^3. Peak concentrations over shorter averaging periods may still be high, both in cities with a high use of coal for domestic heating and when plumes of effluent from power station chimneys fall to the ground (fumigation episodes). Transient peak concentrations of several thousand μg/m^3 are not uncommon. Indoor concentrations of sulfur dioxide are generally lower than outdoor concentrations, since absorption occurs on walls, furniture and clothing and in ventilation systems. An exception is occupational exposure, where concentrations of several thousand μg/m^3 occur regularly.

Data on European concentrations of sulfur dioxide and deposition of other sulfur compounds are based either on national monitoring networks, which are largely concentrated in urban areas, or on cooperative programmes for the study of long-range transport of pollutants. Natural background concentrations of sulfur dioxide in rural areas of Europe are generally below 5 μg/m^3. The use of tall chimneys, which disperse emissions over wide areas, has led to this increasing to above 25 μg/m^{3}in many areas.

Conversion factors

1 ppm (20 °C, 1013 hPa) = 2860 μg/m^3
1 mg/m^3 = 0.350 ppm

Routes of exposure

Inhalation is the only route of exposure to sulfur dioxide that is of interest with regard to its effects on health.

Toxicokinetics

Absorption of sulfur dioxide in the mucous membranes of the nose and upper respiratory tract occurs as a result of its solubility in aqueous media: 1 volume of water dissolves 45 volumes of sulfur dioxide at 15 °C. Absorption is concentration-dependent, with 85% absorption in the nose at 4–6 μg/m^3 and about 99% at 46 μg/m^3. Amdur *(2)* pointed out that at common ambient concentrations of sulfur dioxide, absorption in the upper airways may be inefficient.

Increased flow rates reduce the percentage of inspired sulfur dioxide absorbed in the nose and upper airways, and thus exercise promotes delivery to the smaller airways. Ammonia is found in the mouth (a product of bacterial metabolism) and may play a role in neutralizing acid aerosols. Sulfite and bisulfite are thought to be the major ions formed on absorption of sulfur dioxide. The key reactions are:

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$H_2SO_3 + H_2O \rightarrow HSO_3^- + H_3O^+ \quad (1)$$

$$HSO_3^- + H_2O \rightarrow SO_3^{2-} + H_3O^+ \quad (2)$$

The pKa values of reactions (1) and (2) are 1.86 and 7.2, respectively. The pH of the surface fluid in the respiratory tract is 6.5–7.5, and thus appreciable amounts of both the bisulfite and the sulfite will be present. Absorbed (bi)sulfite is converted to sulfate by molybdenum-dependent sulfite oxidase. The highest concentrations of this enzyme occur in the liver and kidney, while lower levels are found in the lung. The importance of sulfite oxidase in removing absorbed sulfur dioxide from the respiratory tract in humans requires further study although rats, which are deficient in sulfite oxidase, are reported to be more sensitive than control animals to inhaled sulfur dioxide.

The sulfite ion is a reducing agent and reacts with oxidized glutathione in the surface fluid of the airways. Studies of the metabolism of sulfur dioxide have shown that sulfate is also produced from sulfite. The toxicological significance of this process is not yet known.

Health effects

Effects on experimental animals

The effects of sulfur dioxide at ambient concentrations may be conveniently studied by exposure of volunteers. The effects of long-term exposure to sulfur dioxide can, however, be studied only in experimental animals. At concentrations in excess of 28.6 mg/m^3 (10 ppm), prolonged exposure has been shown to produce damage to the epithelium of the airways. This may be followed by epithelial hyperplasia, a dose-related increase in goblet cells and hypertrophy of the submucosal glands. These changes are similar to those seen in chronic bronchitis in humans; prolonged exposure of rats to sulfur dioxide has been used to produce a model of this disease.

In addition to the morphological changes mentioned above, slowing of ciliary transport of mucus has also been demonstrated, although only on exposure to high (858 mg/m^3 or 300 ppm) concentrations of sulfur dioxide. Effects were seen on exposure to much lower concentrations of sulfuric acid. Disruption of ciliary function has recently been shown on exposure of explanted human bronchial tissue to a combination of 572 μg/m^3 (200 ppb) sulfur dioxide and 752 μg/m^3 (400 ppb) nitrogen dioxide.

Studies in a range of species have shown that exposure to sulfur dioxide produces bronchoconstriction. Studies in guinea pigs show responses in the same concentration range as has been shown to affect asthmatic volunteers (about 715 μg/m^3 or 0.25 ppm).

Studies by Amdur *(2)* have demonstrated that the effects of sulfur dioxide may be enhanced by simultaneous exposure to ultra-fine particles. In particular, zinc oxide (2.5–5 mg/m^3) and sulfur dioxide (2860 μg/m^3 or 1 ppm) led to decreased lung volumes and CO diffusing capacity in guinea pigs. These changes were correlated with oedema and damage to epithelial and endothelial cells. Responses increased as the concentration of zinc oxide was raised. The formation of sulfuric acid on the surface of the ultra-fine particles and its delivery to the distal lung have been put forward as explanations of these effects. Re-analysis of air pollution data collected in London in the 1960s has shown a stronger relationship between concentrations of sulfuric acid aerosol and effects on health than with concentrations of black smoke or sulfur dioxide. These findings, and the association between high concentrations of sulfur dioxide, particles and water vapour during the London smogs prior to the 1970s, suggest that the well

reported health effects may have been caused by sulfuric acid delivered on the surface of fine and ultra-fine particles.

Effects on humans

Controlled chamber experiments

A useful guide to the immediate effects of short-term exposures has been provided from the results of controlled chamber experiments with volunteer subjects. These have the advantage of accurate assessment of exposure, freedom from other pollutants and the availability of sensitive laboratory instruments for the measurement of effects, mainly in terms of lung function. Nevertheless, their limitations should also be recognized. Disadvantages include the small numbers of subjects that can be accommodated in any one study, uncertainties as to whether particularly sensitive people have been included, ethical limitations on the use of children, and restrictions placed on physical activity within the confines of the chamber and on duration of exposure *(3)*.

The general features that emerged from the many studies now reported are the following.

1. There appears to be a continuous spectrum of sensitivity to sulfur dioxide, some people being completely unaffected by concentrations that lead to severe bronchoconstriction in others. Asthmatics as a group are particularly sensitive, but otherwise the degree of sensitivity of normal subjects is not obviously related to other characteristics *(3–6)*.

2. Being highly soluble, sulfur dioxide is readily absorbed in the upper respiratory tract and effects are enhanced if penetration to lower regions is increased (through mouth rather than nose breathing and through exercise that raises the amount and depth of inhalation). In chamber studies exercise is introduced with bicycle ergonometers or treadmills *(3,7)*.

3. Response to inhaled sulfur dioxide is rapid, the maximum effect usually being reached within a few minutes *(8)*. Continued exposure does not in general increase the response, and there is a tendency for it to decline gradually *(4)*. Chamber exposures have varied in duration, extending up to 6 hours in some cases *(9)*, but more commonly being 10–15 minutes.

4. Effects are generally short-lived. Lung function returns to normal after some minutes to hours, varying with the individual and the severity of the response.

5. Chamber experiments are usually conducted at room temperature, but some increase in response has been noted, at least among asthmatics, when sulfur dioxide is administered in cold dry air *(10)*.

In view of all these variable features it is difficult to draw a consistent picture of exposure–response relationships, but the findings among normal subjects can be summarized as follows. Reductions in mean lung function values among groups of normal subjects at rest have been seen in 10-minute exposures at 4000 ppb (11 440 $\mu g/m^3$) *(11)* and at 5000 ppb (14 300 $\mu g/m^3$) *(4)*. No significant changes in group mean lung function have been seen below 1000 ppb (2860 $\mu g/m^3$) even with exercise, though there are examples of airway resistance increasing in individuals at that value, with deep breathing *(4)*.

Findings among asthmatics can also be summarized. Such people appear to respond in a similar way to normal subjects, with development of bronchoconstriction, but at lower concentrations. Similarly, there are large variations in sensitivity, and while patients with severe asthma might not necessarily display the greatest sensitivity they would normally be excluded from experimental exposures.

Several studies have shown fairly large changes in mean values of lung function indices with 600 ppb (1716 μg/m^3) and heavy exercise *(11,12)* and with 500 ppb (1430 μg/m^3) and moderate or severe but not light exercise *(7)*. There are not necessarily clear thresholds, and for the purposes of guideline development interest focuses on the lower ranges of concentration i.e. within those liable to occur in the ambient air. Several forms of exposure–response relationship have emerged from the literature *(3)*, each showing decreases in forced expiratory volume (FEV), or increases in airway resistance, on a group mean basis when plotted against $\log_{SO_2}$ concentration. One relatively straightforward example is given in the study by Linn et al. *(13)* examining the dose–response relationship of change in mean FEV_1 with increasing concentrations of sulfur dioxide with exercise (after subtracting the effect of exercise alone) in patients with moderate or severe asthma. Overall, the mean response at 400 ppb (1144 μg/m^3) has been definite though small, at around a 300-ml fall in whereas at 200 ppb (572 μg/m^3) any change has been minimal and similar in magnitude to effects of exercise alone in clean air.

From the information published to date, the overall conclusion is that the minimum concentration evoking changes in lung function in exercising asthmatics is of the order of 400 ppb (1144 μg/m^3), although there is the one example of small changes in airway resistance in two sensitive subjects at 100 ppb (286 μg/m^3). In evaluating this further, judgements are required regarding the clinical significance of such effects, the extent to which particularly sensitive subjects have been represented in the studies, the practical relevance of the enforced exercise required to enhance the effects, and how to relate the short (10- to 15-minute) exposures to the more usual hourly average monitoring data.

Epidemiological studies

Older epidemiological studies (up to about the mid-1980s) assessing the health effects of air pollution, including that caused by sulfur dioxide, have not been considered as providing reliable evidence for the independent effects of sulfur dioxide. Rather, they assessed the effects of the traditional pollutant mixture produced by fossil fuel combustion processes, which included particulate matter and sulfur dioxide as primary pollutants plus secondary particles, including acid aerosols *(1)*.

Although epidemiological studies of air pollution exposure have the advantage of studying the populations of interest (including sensitive individuals) exposed at the usual ambient pollutants levels, and monitoring relevant outcomes (transient or irreversible), they have the drawback that they inevitably study exposure to a pollutant mixture. In recent years, however, more sophisticated statistical methodology has allowed the (at least) partial separation of the effects of individual pollutants via modelling. Furthermore, the large number of published studies is allowing an overall evaluation of the effects of sulfur dioxide in situations with varying pollutant mixes, and in particular with different levels of particulate matter.

In the following sections short-term and long-term effects will be considered separately.

Short-term effects

In this section only epidemiological studies published after 1985 are considered. The majority of these are temporal studies using aggregated data (time-series studies). The reviewed studies have generally assessed the short-term health effects of moderate or low sulfur dioxide levels, most often below the 1987 WHO air quality guideline values *(1)*.

The emphasis placed in the United States on the adverse effects on health of particulate matter, and the debate surrounding that issue, have led to many studies that have only considered (or are greatly focused on) the health aspects, which are thus now better understood. Some recent results, however, indicate that sulfur dioxide has independent (from other measured pollutants) acute adverse health effects. The health effects considered are usually either the total or cause-specific daily numbers of deaths and hospital admissions, mainly for respiratory (specifically chronic obstructive pulmonary disease (COPD) or asthma) or cardiovascular causes.

Mortality studies

Two studies published in 1986 and 1989 concerning data from Athens *(14)* and two French cities, Lyon and Marseilles *(15)*, found an effect on daily mortality only of sulfur dioxide concentrations, while no statistically significant effect of particulate matter (measured as black smoke (BS) in Athens and as total suspended particulate matter (TSP) in Lyon and Marseille) was found. However, the analyses applied in these two studies do not lead to epidemiologically interpretable results and cannot be used in the estimation of dose–response relationships.

On examining the results of 14 studies *(16–29)* assessing the effects on mortality of (among other pollutants) sulfur dioxide, the following conclusions can be drawn. All studies were controlled for the effects of the major potential confounders. All found a positive association between ambient levels of sulfur dioxide and the total daily number of deaths, but it is not always clear to what extent these effects are attributable to sulfur dioxide exposure or to a mixture of pollutants. Some investigators have commented that, although studies that introduce two or more pollutants into a model may produce estimates of the individual effects of the pollutants, it is not clear whether the reported effects in such a multi-pollutant model appear stronger for pollutants that are measured more accurately ("accuracy" here refers to a better representation of the average population exposure) or for those for which the relationships are "causal".

Of the 14 studies assessed, 7 *(23–29)* are part of the Air Pollution and Health: a European Approach (APHEA) project *(30)* and 7 *(16–22)* are independent single studies. In one out of seven of the presented non-APHEA studies *(17)* the sulfur dioxide effect on mortality was not statistically significant in any model, and this was in the city with the lowest observed sulfur dioxide values. In another *(16)*, introducing TSP levels in the model rendered the sulfur dioxide estimate non-significant, while the analysis of sulfur dioxide in the Philadelphia data *(21,22)* gave inconclusive results. In two studies, the sulfur dioxide effect remained the most consistent and statistically significant in two or three pollutant models *(18,19)*, while Wietlisbach et al. *(20)* made no attempt to separate pollutants effects. In the APHEA multicentre European study, two pollutant models were not used in the standardized protocol of analysis *(30,31)*. It is unlikely, however, that the sulfur dioxide effects in these cities reflect the effects of particles because, if this were true, then the sulfur dioxide effect for a specific increase in its level (say, 100 $\mu g/m^3$) would be larger in cities with higher particulate matter

levels. This would happen because a 100-μg/m^3 change in sulfur dioxide would reflect a greater range of particles in a city with a high particulate matter level compared to a city with a low level (taking into account that sulfur dioxide and particulate matter levels are typically positively correlated). When examining the relative risk of total mortality associated with increases in sulfur dioxide levels for nine cities, ordered by the ambient particulate matter level in each city, no monotonic pattern is observed. This evidence should be considered as a strong indication that sulfur dioxide is not acting as surrogate for PM_{10} (particulate matter in which 50% of particles have an aerodynamic diameter < 10 μm) or BS, but does not of course exclude that it may be a surrogate of some unmeasured substance such as ultra-fine particles or sulfates.

Morbidity studies
Eight studies examining the short-term effects of sulfur dioxide exposure on hospital admissions can be assessed *(25,29,32–37)*. Five of these *(25,29,35–37)* are part of the APHEA project. The sulfur dioxide effects are not significant in three studies *(35–37)*, while in one *(32)* they become insignificant in a two-pollutant model. There is a significant 4% increase associated with hospital respiratory admissions in Paris and Milan *(25,29)* and a significant 10% increase in Paris and 6–9% increase in Barcelona for COPD admissions *(25,33,34)*. In Barcelona, the effects remain statistically significant but are lower (2–4%) in two pollutant models that included particulate matter levels.

In both mortality and morbidity studies there has been no consistent threshold observed, and the evidence rather points to the existence of no obvious threshold value for short-term effects of sulfur dioxide. Nevertheless, it should be noted that mean sulfur dioxide levels over the study period in most studies were below the WHO recommended annual value of 50 μg/m^3 *(38)*.

Lung function changes
These effects have generally been assessed using measurements of ventilatory capacity such as $FEV_{0.75}$, FEV_1, forced vital capacity (FVC) or peak expiratory flow (PEF) *(3)*. Small effects on lung function have been observed at low levels of exposure (<300 μg/m^3) but it is difficult to separate the independent effects of sulfur dioxide *(3)*.

Long-term effects
Studies on chronic effects of air pollutants typically compare geographical areas with different levels of air pollution and are thus ecological studies, at least in respect to exposure assessment. Older studies had little information on confounders and did not help to evaluate the health effects of air pollution, and even less that of specific pollutants *(1)*. More recent studies have much better control of confounders by collecting individual data, but are still not very helpful in estimating the effects of specific pollutants.

Several studies have been conducted among children *(3)*. In these studies the annual levels of sulfur dioxide in the most polluted areas were in the range 68–275 μg/m^3 and in the cleanest areas in the range 10–123 μg/m^3. In most studies higher air pollution was associated with increased respiratory symptoms and a small or no reduction in lung function *(3)*. Nevertheless, particulate matter was also present in the study areas (measured either as BS or as TSP) and it was very difficult to separate the effects of each pollutant. A few studies conducted in adults suggest a role for sulfur dioxide exposure in the frequency of wheeze *(39)* and possibly of symptoms (cough or phlegm) *(40,41)*. Some studies were unable to address

the issue of separating the effects of pollutants; others indicated that either particulate matter or sulfate was the most relevant pollutant or pollution indicator *(3)*.

Two cohort studies, conducted carefully and with better control of confounding, provided important evidence that air pollution exposure has chronic effects on mortality. In the Harvard Six cities study *(42)* increased mortality was observed in cities with higher sulfur dioxide levels, but exposure to fine particles had the strongest explanatory value among the pollutants measured. In the other cohort study *(43)* more cities were studied but sulfur dioxide levels were not available. Effects on mortality rates in this study were observed for exposure to sulfate and fine particles.

Evaluation of human health risks

Exposure evaluation

In much of western Europe and North America, concentrations of sulfur dioxide in urban areas have continued to decline in recent years as a result of controls on emissions and changes in fuel use. Annual mean concentrations in such areas are now mainly in the range 20–60 μg/m^3 (0.007–0.021 ppm), with daily means seldom more than 125 μg/m^3 (0.044 ppm). In large cities where coal is still widely used for domestic heating or cooking, however, or where there are poorly controlled industrial sources, concentrations may be 5–10 times those values. Peak concentrations over shorter averaging periods, of the order of 10 minutes, can reach 1000–2000 μg/m^3
(0.35–0.70 ppm) in some circumstances, such as the grounding of plumes from major point sources or during peak dispersion conditions in urban areas with multiple sources.

Health risk evaluation

Short-term exposures (less than 24 hours)

The most direct information on the acute effects of sulfur dioxide comes from controlled chamber experiments on volunteers. Most of these studies have been for exposure periods ranging from a few minutes up to 1 hour. The exact duration is not critical, however, because responses occur very rapidly, within the first few minutes from commencement of inhalation; continuing the exposure further does not increase effects. The effects observed include reductions in FEV_1 or other indices of ventilatory capacity, increases in specific airway resistance, and symptoms such as wheezing or shortness of breath. Such effects are enhanced by exercise, whch increases the volume of air inspired thereby allowing sulfur dioxide to penetrate further into the respiratory tract.

A wide range of sensitivity has been demonstrated, both among normal individuals and among those with asthma, who form the most sensitive group. Continuous exposure–response relationships, without any clearly defined threshold, are evident. To develop a guideline value, the minimum concentrations associated with adverse effects in the most extreme circumstances, that is with asthmatic patients exercising in chambers, have been considered. An example of an exposure–response relationship for such subjects is given by Linn et al. *(13)*, expressed in terms of reductions in FEV_1 after a 15-minute exposure. Only small changes, not regarded as of clinical significance, were seen at 572 μg/m^3 (0.2 ppm); reductions representing about 10% of baseline FEV_1 occurred at about 1144 μg/m^3 (0.4 ppm); and reductions of about 15% occurred at about 1716 μg/m^3 (0.6 ppm). The response was not greatly influenced by the severity of asthma. These findings are consistent with those reported

from other exposure studies. In one early series, however, a small change in airway resistance was reported in two of the asthmatic patients at 286 μg/m^3 (0.1 ppm).

Exposure over a 24-hour period
Information on effects of exposure averaged over a 24-hour period is derived mainly from epidemiological studies in which the effects of sulfur dioxide, particulate matter and other associated pollutants are considered. Exacerbation of symptoms among panels of selected sensitive patients occurred consistently when the concentration of sulfur dioxide exceeded 250 μg/m^3 (0.087ppm) in the presence of particulate matter. Such findings have related mainly to situations in which emissions from the inefficient burning of coal in domestic appliances have been the main contributor to the pollution complex. Several more recent studies, involving the mixed industrial and vehicular sources that now dominate, have consistently demonstrated effects on mortality (total, cardiovascular and respiratory) and hospital emergency admissions for total respiratory causes and COPD at lower levels of exposure (mean annual levels below 50 μg/m^3; daily levels usually not exceeding 125 μg/m^3). These results have been shown, in some instances, to persist when black smoke and TSP levels were controlled for, while in others no attempts were made to separate the effects of the pollutants. No obvious threshold levels could so far be identified in those studies.

Long-term exposure
A similar situation arises in respect of effects of long-term exposures, expressed as annual averages. Earlier assessments examined findings on the prevalence of respiratory symptoms, respiratory illness frequencies, or differences in lung function values in localities with contrasting concentrations of sulfur dioxide and particulate matter, largely in the coal-burning era. The lowest-observed-adverse-effect level of sulfur dioxide was judged to be 100 μg/m^3 (0.035 ppm) annual average, together with particulate matter. More recent studies related to industrial sources, or to the changed urban mixture, have shown adverse effects below this level, but a major difficulty in interpretation is that long-term effects are liable to be affected not only by current conditions but also by the qualitatively and quantitatively different pollution of earlier years. Cohort studies of differences in mortality between areas with contrasting pollution levels indicate that there is a closer association with particulate matter than with sulfur dioxide.

Guidelines

Short-term exposures
Controlled studies with exercising asthmatics indicate that some experience changes in pulmonary function and respiratory symptoms after periods of exposure as short as 10 minutes. Based on this evidence, it is recommended that a value of 500 μg/m^3 (0.175 ppm) should not be exceeded over averaging periods of 10 minutes. Because exposure to sharp peaks depends on the nature of local sources, no single factor can be applied to this value in order to estimate corresponding guideline values over somewhat longer periods, such as an hour.

Exposure over a 24-hour period and long-term exposure
Day-to-day changes in mortality, morbidity or lung function related to 24-hour average concentrations of sulfur dioxide are necessarily based on epidemiological studies in which people are in general exposed to a mixture of pollutants, which is why guideline values for sulfur dioxide have previously been linked with corresponding values for particulate matter. This approach led to a previous guideline value of 125 μg/m^3 (0.04 ppm) as a 24-hour

average, after applying an uncertainty factor of 2 to the lowest-observed-adverse-effect level. In more recent studies, adverse effects with significant public health importance have been observed at much lower levels of exposure. Nevertheless, there is still uncertainty as to whether sulfur dioxide is the pollutant responsible for the observed adverse effects or, rather, a surrogate for ultra-fine particles or some other correlated substance. There is no basis for revising the 1987 guidelines for sulfur dioxide and thus the following guidelines are recommended:

24 hours:	125 μg/m^3
annual:	50 μg/m^3

It should be noted that unlike the 1987 guidelines, these values for sulfur dioxide are no longer linked with particles.

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