

Sulfur Oxides

Sulfur oxides (SO_x) are compounds of sulfur and oxygen molecules. Sulfur dioxide (SO₂) is the predominant form found in the lower atmosphere. It is a colorless gas that can be detected by taste and smell in the range of 1,000 to 3,000 micrograms per cubic meter (µg/m³). At concentrations of 10,000 µg/m³, it has a pungent, unpleasant odor. Sulfur dioxide dissolves readily in water present in the atmosphere to form sulfurous acid (H₂SO₃). About 30% of the sulfur dioxide in the atmosphere is converted to sulfate aerosol (acid aerosol), which is removed through wet or dry deposition processes. Sulfur trioxide (SO₃), another oxide of sulfur, is either emitted directly into the atmosphere or produced from sulfur dioxide and is rapidly converted to sulfuric acid (H₂SO₄).

Major Sources

Most sulfur dioxide is produced by burning fuels containing sulfur or by roasting metal sulfide ores, although there are natural sources of sulfur dioxide (accounting for 35–65% of total sulfur dioxide emissions) such as volcanoes. Thermal power plants burning high-sulfur coal or heating oil are generally the main sources of anthropogenic sulfur dioxide emissions worldwide, followed by industrial boilers and nonferrous metal smelters. Emissions from domestic coal burning and from vehicles can also contribute to high local ambient concentrations of sulfur dioxide.

Health and Environmental Impacts

Periodic episodes of very high concentrations of sulfur dioxide are believed to cause most of the health and vegetation damage attributable to sulfur emissions. Depending on wind, temperature, humidity, and topography, sulfur dioxide can con-

centrate close to ground level. During the London fog of 1952, levels reached 3,500 µg/m³ (averaged over 48 hours) in the center of the city and remained high for a period of 5 days. High levels have been recorded during temperature inversions in Central and Eastern Europe, in China, and in other localities.

Health

Exposure to sulfur dioxide in the ambient air has been associated with reduced lung function, increased incidence of respiratory symptoms and diseases, irritation of the eyes, nose, and throat, and premature mortality. Children, the elderly, and those already suffering from respiratory ailments, such as asthmatics, are especially at risk. Health impacts appear to be linked especially to brief exposures to ambient concentrations above 1,000 µg/m³ (acute exposures measured over 10 minutes). Some epidemiologic studies, however, have shown an association between relatively low annual mean levels and excess mortality. It is not clear whether long-term effects are related simply to annual mean values or to repeated exposures to peak values.

Health effects attributed to sulfur oxides are due to exposure to sulfur dioxide, sulfate aerosols, and sulfur dioxide adsorbed onto particulate matter. Alone, sulfur dioxide will dissolve in the watery fluids of the upper respiratory system and be absorbed into the bloodstream. Sulfur dioxide reacts with other substances in the atmosphere to form sulfate aerosols. Since most sulfate aerosols are part of PM_{2.5} (fine particulate matter, with an aerodynamic diameter of less than 2.5 microns), they may have an important role in the health impacts associated with fine particulates. However, sulfate aerosols can be

transported long distances through the atmosphere before deposition occurs. Average sulfate aerosol concentrations are about 40% of average fine particulate levels in regions where fuels with high sulfur content are commonly used. Sulfur dioxide adsorbed on particles can be carried deep into the pulmonary system. Therefore, reducing concentrations of particulate matter may also reduce the health impacts of sulfur dioxide. Acid aerosols affect respiratory and sensory functions.

Environment

Sulfur oxide emissions cause adverse impacts to vegetation, including forests and agricultural crops. Studies in the United States and elsewhere have shown that plants exposed to high ambient concentrations of sulfur dioxide may lose their foliage, become less productive, or die prematurely. Some species are much more sensitive to exposure than others. Plants in the immediate vicinity of emissions sources are more vulnerable. Studies have shown that the most sensitive species of plants begin to demonstrate visible signs of injury at concentrations of about 1,850 $\mu\text{g}/\text{m}^3$ for 1 hour, 500 $\mu\text{g}/\text{m}^3$ for 8 hours, and 40 $\mu\text{g}/\text{m}^3$ for the growing season (Smith 1981, cited in NAPAP 1990). In studies carried out in Canada, chronic effects on pine forest growth were prominent where concentrations of sulfur dioxide in air averaged 44 $\mu\text{g}/\text{m}^3$, the arithmetic mean for the total 10 year measurement period; the chronic effects were slight where annual concentrations of sulfur dioxide averaged 21 $\mu\text{g}/\text{m}^3$ (Canada 1987).

Trees and other plants exposed to wet and dry acid depositions at some distance from the source of emissions may also be injured. Impacts on forest ecosystems vary greatly according to soil type, plant species, atmospheric conditions, insect populations, and other factors that are not well understood.

Agricultural crops may also be injured by exposure to depositions. Alfalfa and rye grass are especially sensitive. It appears that leaf damage must be extensive before exposure affects the yields of most crops. It is possible that over the long-term, sulfur input to soils will affect yields (OECD 1981; NAPAP 1990). However, sulfur dioxide may not be the primary cause of plant injury, and other pollutants such as ozone may have a greater impact.

Acid depositions can damage freshwater lake and stream ecosystems by lowering the pH of the water. Lakes with low buffering capacity, which could help neutralize acid rain, are especially at risk. Few fish species can survive large shifts in pH, and affected lakes could become completely devoid of fish life. Acidification also decreases the species variety and abundance of other animal and plant life.

Sulfate aerosols, converted from sulfur dioxide in the atmosphere, can reduce visibility by scattering light. In combination with warm temperatures, abundant sunlight, high humidity, and reduced vertical mixing, such aerosols can contribute to haziness extending over large areas.

Materials

Sulfur dioxide emissions may affect building stone and ferrous and nonferrous metals. Sulfurous acid, formed from the reaction of sulfur dioxide with moisture, accelerates the corrosion of iron, steel, and zinc. Sulfur oxides react with copper to produce the green patina of copper sulfate on the surface of the copper. Acids in the form of gases, aerosols, or precipitation may chemically erode building materials such as marble, limestone, and dolomite. Of particular concern is the chemical erosion of historical monuments and works of art. Sulfurous and sulfuric acids formed from sulfur dioxide and sulfur trioxide when they react with moisture may also damage paper and leather.

Ambient Standards and Guidelines

The main goal of almost all the major national and international standards and guidelines produced over the last two decades has been to protect human health. Early research appeared to indicate a threshold or “no-effects” level below which health impacts were negligible for even the most vulnerable groups, such as asthmatics and smokers. Standards were then set below this level to provide a margin of safety. The EU standards recognize the possibility that exposure to both sulfur dioxide and particulate matter may have an additive or synergistic effect on health. (This is also recognized by WHO.) The EU limit value for ambient sulfur dioxide therefore varies depending on the concentration of particulate matter in the ambient air.

Table 1. Reference Standards and Guidelines for Ambient Sulfur Dioxide Concentrations
(micrograms per cubic meter)

Standard or guideline	Annual average		Winter		24-hour		1-hour, sulfur dioxide
	Sulfur dioxide	Associated particulate levels	Sulfur dioxide	Associated particulate levels	Sulfur dioxide	Associated particulate levels	
EU limit values	80 ^a	> 40 ^b	130 ^c	> 60 ^b	250 ^d	> 150 ^b	
	120 ^a	≤ 40 ^b	180 ^c	≤ 60 ^b	350 ^d	≤ 150 ^b	
	80 ^a	> 150 ^e	130 ^c	> 200 ^e	250 ^d	> 350 ^e	
	120 ^a	≤ 150 ^e	180 ^c	≤ 200 ^e	350 ^d	≤ 350 ^e	
USEPA standards	80 ^f				365 ^g		
WHO guidelines	40–60 ^f				100–150 ^d		
WHO guidelines for Europe	50 ^f				125 ^d		350
ECE critical value	10/20/30		20/30				

a. Median of daily values taken throughout the year. b. Black smoke method c. Median of daily values taken throughout the winter. d. 98th percentile of all daily values taken throughout the year; should not be exceeded more than 7 days a year. e. Gravimetric method. f. Arithmetic mean. g. Not to be exceeded more than once a year. Sources: European Community Directive 80/779 (July 5, 1980) and amending Directive 89/427 (July 14, 1989); USEPA 1990; WHO 1979, 1987.

Table 1 summarizes key reference standards and guidelines for ambient SO₂ concentrations.

Recommendations

In the long term, countries should seek to ensure that ambient exposure to sulfur dioxide does not exceed the guidelines recommended by WHO. In the interim, countries should set ambient standards for sulfur dioxide that take into account the benefits to human health and sensitive ecosystems of reducing exposure to sulfur dioxide; the concentration levels achievable by pollution prevention and control measures; and the costs involved in meeting the standards. In adopting new ambient air quality standards or guidelines, countries should set appropriate phase-in periods. Where large differences exist between the costs and the benefits of meeting air quality standards and guidelines, it may be appropriate to establish area-specific ambient standards case by case.

Prior to carrying out an environmental assessment (EA), a trigger value for the annual average concentrations of sulfur dioxide should be agreed on by the country and the World Bank. Countries may wish to adopt EU, USEPA, or WHO

guidelines or standards as their trigger values. The trigger value should be equal to or lower than the country's ambient standard. The trigger value is not an ambient air quality standard but simply a threshold. If, as a result of the project, the trigger value is predicted to be exceeded in the area affected by the project, the EA should seek mitigation alternatives on a regional or sectoral basis. In the absence of an agreed value, the World Bank Group will classify airsheds as moderately degraded if concentration levels are above 80 µg/m³ annual average or if the 98th percentile of 24-hour mean values over a period of one year is estimated to exceed 150 µg/m³. Airsheds will be classified as having poor air quality with respect to sulfur dioxide if either the annual mean value of sulfur dioxide is greater than 100 µg/m³ or the 95th percentile of 24-hour mean value for sulfur dioxide for the airshed over a period of one year is estimated to exceed 150 µg/m³.

In addition, good practice in airshed management should encompass the establishment of an emergency response plan during industrial plant operation. It is recommended that this plan be put into effect when levels of air pollution exceed one or more of the emergency trigger val-

ues (determined for short-term concentrations of sulfur dioxide, nitrogen oxides, particulates, and ozone). The recommended emergency trigger value for sulfur dioxide is 150 µg/m³ for the 24-hour average concentrations.

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