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Introduction

This paper presents a methodology we have developed for assessing human health effects due to the emission of sulfur dioxide from a single fossile fuel power plant. This has been a difficult task to attempt in the past, containing great uncertainty; however, a new EPA model of health effects has recently been published and is, in our opinion, the best and most careful model of health impact of air pollution to date (1). The EPA model has current best judgements of impacts; it does not include all health effects thought to be related to air pollution. Our methodology was developed around this model using detailed air pollution data from Wisconsin.

The EPA model is based on two main points. The first is that acid sulfates, not SO_2, are the root cause of the health effects, and that the important averaging time is one day (24 hours). The second is the well established observation that the frequency of occurance of different levels of pollution in the course of a year is distributed log-normally (2). The output of the model is the excess mortality in the population and the excess morbidity in the population for certain ailments and population subgroups due to the exposure to acid sulfates.

<u>Health Impact Model</u>

There are two parts to the health impact model: (1) the conversion of SO_2 measurements to levels of acid sulfates, and (2) the dose-response functions of the health impacts. Most air pollution monitoring stations only measure SO_2; therefore, a relationship for the conversion of SO_2 to acid sulfates must be established. The EPA report listed two possible conversion constants for 24 hour sulfate levels based on studies in several U.S. cities.

sulfate ($\mu g/m^3$) = 9 + .03SO_2($\mu g/m^3$)	1959-1960 Nashville Study (r = .8)
sulfate ($\mu g/m^3$) = 9 + .05SO_2($\mu g/m^3$)	1966-1967 NASN data 8 inland cities (r = .5)

The Nashville study is more representative of Wisconsin, as intruding background sulfates were not a problem (3). The same conversion equation is used for both the annual average SO_2 and the 24 hour average SO_2 conversion rates to sulfate (4).

Five dose-response functions linking acid-sulfate aerosol exposures to selected adverse health effects are given in the EPA report and reproduced here in Table I. The main features are that there is a threshold level, below which there are no health impacts (a point that has been hotly debated, but the evidence presented in the EPA report supports this conclusion), and that above the threshold the response is linear. It should be noted that for all cities studied, there was particulate matter (P.M.) also present, so that these relations have folded into them some synergistic interaction between P.M. and acid-sulfates (which is

Adverse Health Effect	Threshold Concentration of Suspended Sulfates and Exposure Duration	Slope	Intercept
Increase Daily Mortality (4 studies) (acute episodes)	25 $\mu g/m^3$ for 24 hours or longer	0.00252	-0.0631
Aggravation of Heart and Lung Disease in Elderly Patients (2 studies)	9 $\mu g/m^3$ for 24 hours or longer	0.0141	-0.127
Aggravation of Asthma (4 studies)	6-10 $\mu g/m^3$ for 24 hours or longer	0.0335	-0.201
Excess Acute Lower Respiratory Disease in Children (4 studies)	13 $\mu g/m^3$ for several years	0.0769	-1.000
Excess Risk for Chronic Bronchitis (6 studies)			
Non-Smokers	10 $\mu g/m^3$ for up to 10 years	0.1340	-1.42
Cigarette Smokers	15 $\mu g/m^3$ for up to 10 years	0.0738	-1.14

Table I

better than if it were for sulfates alone). Also, there is no expressed confidence that these dose-response relations hold in cities with large steel or magnesium works or in cities with photochemical smog (1).

Dosage Model

For this part of the model, detailed data from Wisconsin was used, but we feel that the results are generally applicable and the Wisconsin numbers will be presented in that light. The dose-response relations require 24 hours average concentrations for each day of the year and the arithmetic annual average concentration. Given that the daily average concentrations are distributed log-normally, then a relationship exists between the annual average concentration (arithmetic and geometric) and the geometric standard deviation, S, to allow computing of the daily averages. We have developed an empirical relationship for S, as a function of distance from the plant and as a function of angle around the plant, based on actual Wisconsin data (5,6).

In the region around high and medium-high ground-level peaks in the arithmetic annual average, where the gradients in the ground-level concentration are large, S is also relatively large - approximately $5 \mu g/m^3$ for SO_2. At relatively large distances from the plant (e.g., 50-80 km) where the plume is no longer distinguishable as an entity above the rest of the background, S is approximately $1.75 \mu g/m^3$ for SO_2. For the intermediate and lower level peaks in the ground level concentration S has an intermediate value of approximately $3 \mu g/m^3$. Beyond the ground-level peaks around the plant the concentration decreases approximately as an exponential, leading one to expect that S will also decrease nearly as an exponential to the value $1.75 \mu g/m^3$. The location and extent of the regions of high concentration gradients depends on the meteorology and the surface roughness (whether the plant is in a rural or urban setting) (7). For southern Wisconsin and a power plant stack of 152m (typical for Wisconsin) we find the following:

(1) Total angular extent of high and medium-high peaks	~ 90°	, both urban and rural settings
(2) Extent of high gradients away from the power plant	~ 0-15km ~ 0-10km	, rural setting , urban setting

Thus we form the relation for S as shown in Figure 1 for a rural power plant.

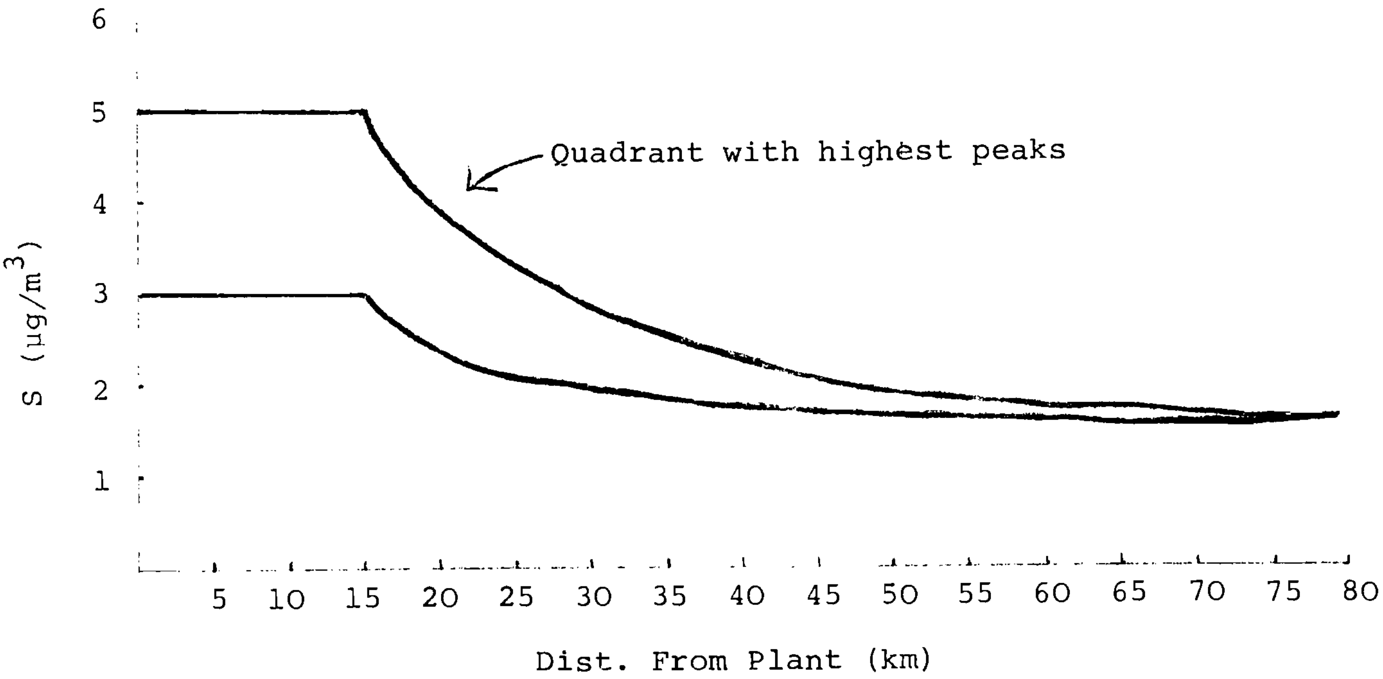

Figure 1

We have pushed all the regions of high peak concentration into one quadrant here, but that is not at all necessary.

Putting It All Together

The geometric mean, M, the geometric standard deviation, S, and the arithmetic average, A, for a normal distribution are related according to the equation (8),

$$M = A \exp\left[-\frac{1}{2}(\ln S)^2\right] ,$$

where the dispersion calculation above (7) gives us A and we have developed a model for S. A normal distribution with a mean of zero is given by

$$f(y) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{1}{2} y^2\right] .$$

The normal cumulative function, $\Phi(y)$, is the integral of f(y).

$$\Phi(y) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y} \exp\left[-\frac{1}{2} y'^2\right] dy'$$

This integral approaches unity as y goes to infinity. With a log-normal distribution, the variable y becomes

$$y = \frac{\ln C(p) - \ln M}{\ln S} ,$$

where C(p) is the concentration that is exceeded with probability p. The normal cumulative function connects C(p) and p.

$$\Phi\left(\frac{\ln C(p) - \ln M}{\ln S}\right) = 1 - p$$

The concentration that will be exceeded by a probability p is determined by the inverse function, Φ^{-1}.

$$\Phi^{-1}(1 - p) = \frac{\ln C(p) - \ln M}{\ln S}$$

Solving for C(p) gives

$$C(p) = M \cdot S^{\Phi^{-1}(1 - p)} .$$

The value of p for the day with the i^{th} highest concentration is

$$p_i = \frac{i - \frac{1}{2}}{365}, \quad i = 1,2,\ldots,365 .$$

The $\frac{1}{2}$ indicates that the midpoint of the probability spanning one day's time is associated with that entire day. This is a very good approximation, except possibly in the neighborhood of the wings of the distribution. The highest concentration corresponds to i=1. These equations plus Normal Probability Function Tables are all that is necessary.

Example: Suppose A is $5\mu g/m^3$ and S is $5\mu g/m^3$. Then M is $1.37\mu g/m^3$. The calculations for three days of the year for this data are outlined below.

Worst Day

$$1 - p = 1 - \frac{1 - \frac{1}{2}}{365}$$

$$= 0.99863$$

$$\Phi^{-1}(0.99863) = 2.99 \quad \text{(from tables)}$$

$$C(0.00137) = 1.37 \cdot 5^{-2.99}$$

$$= 169\mu g/m^3$$

Mean Day

$$1 - p = 1 - \frac{183 - \frac{1}{2}}{365}$$

$$= 0.5$$

$$\Phi^{-1}(0.5) = 0.0$$

$$C(0.5) = 1.37 \cdot 5^{0}$$

$$= 1.37\mu g/m^3$$

Best Day

$$1 - p = 1 - \frac{365 - \frac{1}{2}}{365}$$

$$= 0.00137$$

$$\Phi^{-1}(0.00137) = -2.99$$

$$C(0.99863) = 1.37 \cdot 5^{-2.99}$$

$$= 0.011 \mu g/m^3$$

In this manner the daily distribution for the concentration values around the power plant can be determined.

The dose-response relationships are best experessed in terms of SO_2 concentration, since most measurements and dispersion calculations to date are working with SO_2. We have done this for the five relationships above, using the Nashville study, and outline below the procedure for calculating the health impacts.

1. Excess daily mortality

Fatalities due to acute SO_2 exposure during air pollution episodes are included here and associated with 24 hour SO_2 concentrations. Excess mortality due to chronic exposure is not included. The fractional excess mortality, $F_1(i)$, for the i^{th} day is given by

$$F_1(i) = -0.0404 + 0.000076 C_{24}(i) \quad ,$$

where $C_{24}(i)$ is the 24 hour SO_2 concentration of day i. The threshold for any effect is about 530 g/m^3, a very high concentration for a single power plant. The excess mortality is calculated by accumulating the $F_1(i)$ for each day the 24 hour SO_2 concentration is above the threshold.

$$E_1 = d \cdot P_r \frac{1}{365} \sum_{i=1}^{365} F_1(i) \quad , \text{ for } C_{24}(i) > 530\mu g/m^3,$$

where

E_1 = excess mortality (percent)

P_r = population exposed (at risk)

d = death rate (deaths per person per year) .

2. Aggravation of heart and lung disease

The population at risk, P_r, is persons aged 65 and over with pre-existing heart and lung disorders. The excess days of aggravation, $F_2(i)$, turn out to be directly proportional to SO_2 concentrations for the case, i.e., there is no threshold.

$$F_2(i) = 0.000423C_{24}(i)$$

Typically, in the U.S., these elderly people suffer one day of aggravation out of five without any SO_2 exposure. Thus the excess days of aggravation per year is

$$E_2 = 0.2P_r \sum_{i=1}^{365} F_2(i) \quad .$$

$$= 8.46 \times 10^{-5} P_r \sum_{i=1}^{365} C_{24}(i)$$

$$= 0.0309 P_r C_{365} \quad ,$$

where C_{365} is the annual arithmetic mean SO_2 concentration in $\mu g/m^3$.

The fact that no threshold exists makes it possible to use the annual arithmetic mean.

3. Aggravation of asthma

The population at risk, P_r, is in this case the total number of people in the population with asthma. The fractional excess asthma attacks is

$$F_3(i) = 0.00101C_{24}(i) \quad .$$

Again there is no threshold for SO_2. The average number of attacks per year in the U.S. is seven. Therefore, the excess asthma attacks per year, E_3, is

$$E_3 = \frac{0.7}{365} P_r \sum_{i=1}^{365} F_3(i)$$

$$= 1.937 \times 10^{-5} P_r \sum_{i=1}^{365} C_{24}(i)$$

$$= 7.07 \times 10^{-3} P_r C_{365} \quad .$$

4. Excess acute lower respiratory disease in children

The correlation for excess acute lower respiratory disease is in terms of the <u>annual arithmetic mean</u> SO_2 concentration and population at risk, P_r, is children aged 0-13. For this case the fractional excess morbidity, F_4, is

$$F_4 = -0.308 + 0.00231C_{365} \quad .$$

The indicated threshold is $133\mu g/m^3$ for the annual average SO_2

concentration. The normal incidence rate in the U.S. is about 6 cases per 100 children per year. The total excess respiratory disease in children, E_4, is

$$E_4 = \frac{6}{100} P_4 F_4 , \qquad \text{whenever } C_{365} > 133\mu g/m^3 .$$

5. Excess risk for chronic bronchitis

The risk of chronic respiratory disease in adults aged 21 and over is related to the <u>annual arithmetic mean</u> SO_2 concentration.

$$F_5 = -0.214 + 0.00402 C_{365} , \qquad \text{for non-smokers}$$

$$F_6 = -0.476 + 0.00221 C_{365} , \qquad \text{for smokers}$$

The threshold for effects is about $53\mu g/m^3$ for non-smokers and $215\mu g/m^3$ for smokers. About 2 percent of non-smoking adults and 10 percent of smoking adults suffer from chronic respiratory disease symptoms. The excess non-smokers and smokers exhibiting these symptoms due to SO_2 exposure is

$$E_5 = 0.02 P_r F_5 , \qquad \text{whenever } C_{365} > 53\mu g/m^3$$

$$E_6 = 0.10 P_r' F_6 , \qquad \text{whenever } C_{365} > 215\mu g/m^3 .$$

The reader is now left with the decision how to apply the model. There are two sets of data needed: (1) the annual arithmetic average SO_2 concentrations around the power plant, and (2) the distribution of the population at risk around the plant. One possible method that has been used by one of us is to use a model power plant and model population distributions (9).

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