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BENEFITS OF POLLUTION CONTROL: THE SO_2 CASE*

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ABSTRACT

This paper reviews damages from sulfur dioxide, comparing national estimates with micro estimates, in common dollar units of account. The damages monetized are changes in mortality rates, morbidity, material soiling and corrosion, and agricultural crop yields. Other impacts such as aesthetics, visibility, and animal mortality and morbidity, are not explicitly considered due to limited knowledge concerning the impacts of SO_2 for these damage categories.

Sulfur dioxide standards for various states and for the U.S. as a whole were originally set by state and federal authorities on largely intuitive grounds, with little attention being given to the relative magnitudes of costs and benefits. Recently hearings reassessing the appropriateness of the regulations have begun to take place as a response to oil price increases, limited success of sulfur removal systems, and shortages of both natural gas and low-sulfur coal. In the present study, the literature on sulfur dioxide damages is surveyed, with estimates measured in a common dollar unit of account as necessary for benefit-cost comparisons.

*This study, conducted while both authors were at the University of Chicago, is based upon the authors' Chapter 2 of Alan S. Cohen, "An Economic Evaluation of Proposed Amendments to the Illinois Sulfur Dioxide Regulations," IIEQ (Illinois Institute for Environmental Quality), No. 77/36 (October, 1977).

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The sulfur dioxide damages monetized in this report are changes in mortality rates, morbidity, material soiling and corrosion, and agricultural crop yields. Other impacts, such as aesthetics, visibility, and animal mortality and morbidity, are not explicitly evaluated in monetary terms because of limited knowledge concerning these impacts. Benefits of a regulation are defined as reductions in these pollution damages.

A number of experts feel that sulfates are a greater environmental problem than SO_2. Unfortunately, ambient sulfate levels are not routinely measured and reliable dispersion models for sulfates are not available. As a result an explicit analysis of the benefits of changes in sulfate levels that may occur with changes in SO_2 emissions is not possible at this time.

All monetary figures presented in this report are expressed in 1976-77 (Dec.-Jan.) dollars. A detailed list of sources of SO_2 damages is provided in the Appendix.

BENEFITS OF POLLUTION CONTROL

The benefits of SO_2 abatement are largely the result of avoiding physical damages that would occur at higher pollution levels. These damages are of three principal types: mortality, morbidity, and materials damage. Other damage categories which have been discussed in the literature include vegetation, livestock, ecosystems, visibility, and aesthetics; of these, vegetation damages, which have been most extensively analyzed, are considered in this study.

The methodological approach taken here is to compare, when possible, the findings of a number of studies of national SO_2 damages with the marginal damage coefficients for SO_2 derived on a micro scale by Cohen, Fishelson, and Gardner [1].[1] The varied methodologies of the national studies provide an opportunity to independently support or invalidate the micro findings. Table 1 lists the damage coefficients generated by Cohen, *et al.*, adjusted to account for inflation.

Examined in the remainder of this study are mortality damages; morbidity costs, principally those due to cardiac and respiratory difficulties associated with exposure to SO_2 (empirical findings corroborating morbidity findings are discussed in a recent paper by Fishelson and Graves [2]) and vegetation damages. Throughout, physical impacts are first described, followed by a discussion of the most plausible methods of monetizing these impacts to facilitate the comparison of marginal benefits to marginal dollar costs of pollution abatement.

[1] Because of the peripheral concern with particulates in the study underlying this report, the particulate damage coefficients were not checked.

Table 1. Table 1. Damage Coefficients

	Damage Coefficients $[\$/\mu g/m^3)/person/yr]$ [a,b]	
Damage Category	*Particulates*	*Sulfur Dioxide*
Mortality	0.294	0.294[c]
Morbidity	0.721	0.721
Materials	2.32	0.824
Total	3.33[d]	1.84

[a] Calculated from Cohen, A. S., G. Fishelson, and J. Gardner [1].
[b] Based on an average household size of 2.7 persons. The numbers were inflated to 1976-77 dollars using the consumer price index. Pollutant concentrations are annual arithematic means.
[c] Cohen, et. al., reported this value as a zero, reflecting an absence of adequate data on the rate at which SO_2 reduction reduces death rates. Here the SO_2 mortality damage is assumed equal to the particulate mortality damage as suggested in B. C. Liu, and E. S. Yu?
[d] Expenditures diverted from other uses are not included in this total.

MORTALITY

Many studies have demonstrated an association between changes in sulfur dioxide levels and direct changes in total mortality and premature and excess deaths. The total mortality rate is defined as the number of deaths in an area per unit time per population at risk, e.g., deaths per year per 10,000 persons. Premature deaths are related to reductions of longevity, while excess deaths are the number of deaths over a period of time that can be attributed to air pollution.

Perhaps the most philosophically difficult task involved in estimating the economic value of the effects of air pollution on mortality is to assign a dollar value to premature deaths. However, a dollar value is needed to enable quantitative comparison of mortality damages to other types of damages. For more details on this point see Cohen, *et al.* [1].

A number of approaches have been used to estimate the economic value of life, the oldest being to calculate foregone earnings. However, this method ignores the benefits of leisure hours, puts zero value on the lives of retired persons or persons not employed outside the home, and does not account for the consumer surplus of living. Recent analyses have examined revealed perferences in the market, particularly those involving small changes in the probability of death in risky situations. Studies of premiums paid in risky occupations [3] and of seat belt usage [4], suggest that self-assessed life value (implied from the risks voluntarily taken) is on the order of \$300,000 for a young individual with a long life expectancy. This evaluation approach, and the resulting numbers, are not applicable to situations in which the probability of death is very large. However, for relatively distant probabilities of death (as with seat belts, smoking, fire and police protection, participation in certain activities), people routinely indicate implied values of life well within the suggested range. This value of life, assuming a cost of capital of 10 per cent, implies a cost of $30,000 for a reduced life expectancy of one year and $78 for a loss of one day.

Additional information required to use the revealed preference approach is the number of individuals affected and the expected number of days of reduced life expectancy due to exposure to various levels of SO_2. Many studies indicate that those with the weakest cardio-pulmonary systems–the aged and infants–are most affected by air pollution. Since most damages occur in the elderly groups, and those in the young groups who are affected (weaker infants) may, for non-pollution reasons, not have had the normal life expectancy for their cohort, the expected reduction in longevity is probably small.

Two major studies estimate changes in mortality rates due to air pollution. Lave and Seskin used linear least squares regression methods to estimate the effects of sulfate pollution on the total (unadjusted) mortality rate [5]. Using 117 SMSAs in 1960, 117 SMSAs in 1969, 26 SMSAs from 1960 through 1969, and Chicago SMSA daily observations of SO_2 for 1965, they found that a 1 per cent reduction in sulfate and particulate levels (SO_2 alone for the Chicago study) was associated with, respectively, 0.091%, 0.116%, 0.090%, and 0.108% reductions in the mortality rate. Unfortunately, Lave and Seskin fail to disclose the absolute level of sulfur oxides upon which the 1 per cent change was based; therefore a marginal damage coefficient in terms of $\mu g/m^3$ levels is not directly inferrable.

North and Merkhofer also estimated a linear damage function, using the results of seven epidemiological studies [6]. Their "best judgment threshold" functions were approximated subjectively, and do not promise the best mathematical fits. They show that an increase from 16 to 17 $\mu g/m^3$ of suspended *sulfate* concentration in the greater New York metropolitan area implies a 0.0192% increase in the yearly mortality rate of 102.6/10,000. For the 11.5 million persons in the New York metropolitan area, this represents about twenty-three excess deaths due to the 1 $\mu g/m^3$ increase in sulfate concentration. An upper bound estimate of the mortality damage coefficient can be estimated by assuming all twenty-three deaths are to infants who would have had a normal life expectancy in the absence of the sulfate increase, i.e., the economic loss is $300,000 per person affected. Using this assumption the damage coefficient is $0.591 (0.591 = 22.66 · $300,000)/11,500,000) per person due to a 1 $\mu g/m^3$ increase in suspended sulfate concentration. However, for an average loss in longevity of one year (probably still high) the damage coefficient would only be $0.059/($\mu g/m^3$ SO_4)/person/yr. Care must be taken, however, in extrapolating a marginal damage figure from a highly polluted area such as that surrounding New York City or in comparing a 1 $\mu g/m^3$ change in sulfates to a 1 $\mu g/m^3$ change in SO_2. Both of these cautions would suggest that the damage estimates may be high if non-linearity of damages is important and if sulfates are more damaging than SO_2.

In the Liu and Yu study [7], total mortality damages were estimated for the forty SMSAs with annual average sulfur dioxide concentrations above 25 $\mu g/m^3$ This particular threshold was employed for two reasons: it was considered to represent the average SO_2 level in rural areas, and it was "considered to be the 'mean' of the tolerable threshold distribution of all individuals in the SMSA." Other distinguishing features of this study are the use of residuals and non-linear functional forms in the dose-response function, and the application of various econometric techniques. The resultant yearly value of foregone future full income (using a 4% discount rate) is $1.2687 billion. The average sulfur dioxide concentration for the forty SMSAs was 47.95 $\mu g/m^3$ and the population at risk in 1970 was 67.093 million. Using this information, we arrive at a marginal mortality damage coefficient of $0.394/person/$\mu g SO_2/m^3$)/year.

Cohen *et al.* [1], using Lave and Seskin's 1960 coefficients estimated the change in life expectancy for a 1 $\mu g/m^3$ change in particulate concentration. They combine this information with data on average earnings, growth of average earnings (2%), labor force participation rates, and premature illness and burial costs. They arrive at a figure of $0.76 per household, or about $0.294 per person per $\mu g/m^3$ of particulate matter (annual arithmetic mean). If mortality damages due to particulates are of about the same magnitude as those due to SO_2 as has been suggested, the Cohen *et al.*, estimate for particulates provides a rough estimate of SO_2 damages as well.

MORBIDITY

Several diseases, especially respiratory and cardiac ailments, have been shown to exhibit consistent dose-response relationships with air pollution levels. Adverse health effects appear equally likely to result from short exposure to high pollutant concentrations or long exposure to lower concentrations [8]. Some interesting new morbidity studies include (1) controlled experiments yielding dose-response relationships between air pollution and conditions such as pulmonary flow resistance in guinea pigs [9], and (2) hospitalization rates and costs analyses [10]. Additional physical morbidity impact studies are summarized in the Appendix.

After summarizing the extensive Community Health and Environmental Surveillance System (CHESS) studies, Liu and Yu present annual morbidity damages in forty SMSAs [7]. They quantify both direct (physician visit, hospitalization, and drug costs) and indirect (output and opportunities foregone costs, assumed to be 2.4 times the direct costs, as estimated by Jaksch [11]. At least two conservative assumptions ensure a "low" estimate of damages:

(1) each pollution-related morbidity incidence was assumed to result in only one physician visit, and (2) if hospitalization is required, each patient was assumed to stay only one day. The result is total annual morbidity costs due to SO_2 in the forty SMSAs of $137.08 million. Their per capita marginal morbidity damage coefficient is $0.0426/person/($\mu gSO_2/m^3$)/year, which is a lower bound figure. This figure is arrived at by dividing the $137 million figure by the number of people in the SMSAs considered (67,093,000) and by the average SO_2 concentration level, 47.95.

North and Merkhofer [6] examined four types of diseases and assigned monetary values as follows: one-day aggravation of heart and lung disease symptoms, $20; one asthma attack, $10; one case of child's lower respiratory disease, $75; and one case of chronic respiratory disease, $250. Basing their dose-response functions on the results of twenty specific studies, they arrive at morbidity damages of $19,853,400 (dollars are for an unspecified recent year) for a change in annual average sulfate concentration from 16 to 17 $\mu g/m^3$, i.e., a 1 $\mu g/m^3$ change in the sulfate level. With a greater New York metropolitan area population at risk of 11.5 million, this translates into a marginal damage coefficient of $1.72/person/($\mu gSO_4/m^3$)/yr.

Cohen *et al.* arrive at a figure, equivalent to $0.72/person/($\mu g/m^3$)/year, which is a combination of results from Lave and Seskin [5,12] and Schrimper [13]. The estimate represents reduced treatment costs for selected morbidity indices: cancer other than in the respiratory tract, and respiratory and cardiovascular diseases.

MATERIALS

Damages to materials, particularly paint and certain metals, take the form of deterioration, fading, and soiling. Soiling damage is not considered here explicitly because it is mainly due to particulates, with relatively little damage caused by sulfur dioxide. Possible synergistic interactions between air pollution and relative humidity are also factors in materials damage. Examples of physical impact studies for material damages are provided in the Appendix.

The most comprehensive, most cited, and most modified materials damage study is Salmon's 1970 report [14]. The EEH report used this study as a basis for estimating the influence of sulfur oxides [15]. Salmon tried to determine the most economically significant materials exposed to air pollution, deterioration rates of these materials, and resulting economic loss of each material. (Data on individual material damages came from interviews and literature surveys.) Of Salmon's modified list of thirty-two materials (representing 40% of all materials exposed to air pollution), thirteen suffer negligible damages due to sulfur oxides. The remaining nineteen materials accounted for an estimated $4,185.5 million of damage in 1970. If we assume materials are in direct proportion to population (203,736,000 U.S. population in 1970), this translates to marginal material damages of \$0.428/person/$\mu gSO_2/m^3$)/year (assuming Liu and Yu's 1970 sulfur dioxide level of 47.95 $\mu g/m^3$). It should be noted that these figures represent only a portion of all materials exposed to air pollution, and may therefore underestimate materials damage. However, they may at least partly represent potential, not actual damages, which suggests an overestimate in that non-replacement "losses" may not be incurred as an actual loss of output.

In two separate reports, Waddell [16] and Barrett and Waddell [17] estimate the national damages to materials by further modifying Salmon's study [14], substituting more intensive studies [18–22] for certain materials. After eliminating the appropriate materials from Salmon's list, Waddell arrives at a total damage to all materials of \$3.22 billion. Barrett and Waddell derive a figure for damage to all materials of \$6.957 billion. These two studies effectively establish upper and lower bounds to Salmon's \$5.563 billion figure for damages to all materials (\$4,185 billion for materials affected by sulfur dioxide). Hence greater confidence is attached to the marginal coefficient of materials damage due to sulfur oxides.

Cohen *et al.* estimate material damages in terms of household maintenace. They indicate that particulates are primarily responsible for soiling maintenance, while sulfur dioxide produces annual damages related to exterior and interior painting of residences of \$2.14 per household, or \$0.82 per person per year for the Chicago metropolitan area, using the 1970 census tract estimate of 2.7 persons per dwelling unit in the Chicago SMSA. This is slightly higher than the estimate obtained from the Salmon study.

VEGETATION

Air pollution damage to plants occurs in two major forms: visible injury, which may or may not involve an economic loss (ornamental vegetation is particularly susceptible to damage); and subtle injury, which can only be detected by a drop in yield or quality. Climatological conditions (relative humidity, sun exposure) also may interact with pollutants in a manner which is difficult to predict. The agricultural impact studies listed in the Appendix attempt to compute dose-response and threshold relations.

Statewise and national-level estimates of vegetation damages were reviewed. The derivation of national estimates using crop statistics, pollution levels, and meteorological data is in its infancy, with the reports of Benedict *et al.* [23,24], providing the basis for further study. For 679 U.S. counties likely to have plant-damaging pollution levels, these studies estimate county crop and ornamental values and individual plant sensitivities, and derive county, state, and national damage estimates for three types of air pollutants. Total national damage due to sulfur dioxide was \$6.072 million for crops and \$5.52 million for ornamentals. Many of the sensitivity and damage estimates are "educated guesses," only replacement costs of ornamentals were included, and little attempt was made to measure subtle or non-visible injuries to plants. These national damages are low, resulting in negligible national marginal damage coefficients, but specific highly-polluted areas may receive substantial damage, particularly to ornamentals.

According to the National Environmental Research Center as reported in the EEH study, corn is resistant to injury [25]. This is further substantiated by studies already referred to which list no corn loss in the U.S. due to sulfur dioxide. Soybeans, wheat, and oats, depending on the variety and strain, are all classified as sensitive to SO_2 [25,26]. Furthermore, the Benedict reports assign damages to these crops of 5 per cent of their value in the counties with highest SO_2 levels [23,24].

Hence, because of the seemingly small effects of SO_2 on vegetation, no detailed analyses of the economic damages to vegetation are provided in this report.

SUMMARY

Table 2 summarizes the estimates of the marginal benefits associated with a (1 $\mu g/m^3$)/person/year reduction in SO_2 for the benefit categories previously discussed. Cohen *et al.* indicate that their itemized damage coefficients are high. The literature survey presented here supports their assertion. Yet, for damage evaluation purposes the range of $1.0 - $2.0 seems to be the reasonable one.

Table 2. Comparison of SO_2 Damage Coefficients

	Damage Coefficients [$/$\mu g/m^3$)/person/yr]	
Damage Category	*Literature Survey*	*Cohen* [a]
Mortality	0.394	0.294
Morbidity	0.100	0.721
Materials	0.428	0.824
Total	0.922	1.84

[a] From Cohen, A.S., G. Fishelson, and J. Gardner, Residential Fuel Policy and the Environment [1].

Appendix

Benefit categories	Level of information								Explanatory remarks
	Qualitative benefit assessment	Quantitative Benefit Assessment							
		Reference	*Amount of benefit*	*Units of measure*	*Range of benefit uncertainty*	*$ value*	*Range of $ uncertainty*		
Human health	Premature deaths per year	1	0.0192	Percentage points decrease in % of cases attributable to SO_4					The decrease in adverse health effects in New York due to a drop in annual average suspended sulfate concentration from 17 $\mu g/m^3$ to 16 $\mu g/m^3$ (standard deviation of daily concentration = 5.6 $\mu g/m^3$). The figures are derived from a combination of expected frequency distributions of suspended sulfate concentrations with dose response curves, which are fitted by assuming a linear threshold relationship of the results of various epidemiological studies. The range of values was arbitrarily chosen. The population at risk in the New York metropolitan area was 11.5 million.
			22.7	Decrease in number of cases	+23.3 -20.4	0.681m*	+2.04m -0.61m		
	Aggravation of heart and lung disease	1	1.662	Percentage points decrease in % of cases attributable to SO_4					
			0.406	Million person days per year	+0.414 -0.365	8.12m	+24.36m -7.31m		
	Asthmatic attacks	1	3.35	Percentage points decrease in % of cases attributable to SO_4					
			0.0841	Million cases per year	+0.084 -0.0757	0.841m	+2.523m -0.757m		
	Lower respiratory disease in children	1	7.69	Percentage points decrease in % of cases attributable to SO_4					
			9.9	Thousand cases per year	+9.90 -8.91	0.743m	+2.23m -0.67m		
	Chronic respiratory disease symptoms	1	11.10	Percentage points decrease in % of cases attributable to SO_4					

Appendix (Cont'd.)

Benefit categories	Qualitative benefit assessment (Level of Information)	Reference (Quantitative Benefit Assessment)	Amount of benefit	Units of measure	Range of benefit uncertainty	$ value	Range of $ uncertainty	Explanatory remarks
			40.6	Thousand cases, point prevalence	+40.6 -36.5	10.15m	+30.45m -9.14m	
	Irritation symptoms arising from acute air pollution episodes	2	75-100	% of symptoms eliminated		Not known		"Rough" estimates of health benefits realizable by control of sulfur dioxide, suspended sulfates and suspended particulates, culled from the EPA CHESS reports (see Refs. 3 and 4). Population affected varied from 4 million to 50 million.
	Impairment of ventilatory function	2	Subtle improvement			Not known		
	Symptom aggravation in elderly	2	10-30	% fewer reported cases		150-800m		
	Asthma attacks ($15 per attack)	2	10-50	% fewer reported cases		50-300m		
	Acute lower respiratory ($11 per restricted activity day)	2	10-40 RADS	% reduction in RADS or visits		400-1500m		
			20-50 Physician visits					
	Chronic bronchitis	2	20-40	% reduction in prevalence		300-600m		
	Excess chronic bronchitis (above non-smoker rate)	4	1.2	% due to air pollution				Figures for white males in a less polluted community in Chicago.
			13.4	% due to smoking				
	Cough symptoms from daily SO_2 ppm:			% person days illness of study group				Study group made up of patients who kept 3-month disease symtom diaries; the figures given are 3-month averages of these.
	0 -0.09		20.3					
	0.1 -0.19		23.7					
	0.2+		29.3					
	Dyspnea symptoms from daily SO_2 ppm:	5		% person days illness of study group				
	0 -0.09		32.3					
	0.1 -0.19		34.3					
	0.2+		38.0					

Purulent sputum from daily SO_2 ppm:	5		% person days illness of study group			
0 -0.09		21.0				
0.1 -0.19		26.7				
0.2+		32.3				
Antibiotic use attributable to daily SO_2 ppm:	5		% person days illness of study group			
0 -0.09		41.0				
0.1 -0.19		43.7				
0.2+		55.0				
Total cardiovascular deaths due to average SO_2 ppm (tertiles):	5		Average number of deaths per day			Study is for Chicago males age 55 and over. Each category displays a sharp rise at the upper tertile of SO_2 concentration. Total number of deaths for each category range from 16 for bronchitis and emphysema to 640 for cardiovascular.
0.08		25.1				
0.17		25.4				
0.29		33.4				
Total coronary heart deaths due to average SO_2 ppm (tertiles):	5		Average number of deaths per day			
0.08		20.0				
0.17		17.7				
0.29		25.5				
Total respiratory deaths due to average SO_2 ppm (tertiles):	5		Average number of deaths per day			
0.08		1.7				
0.17		1.6				
0.29		3.5				
Bronchitis and emphysema deaths due to average SO_2 ppm (textiles):	5		Average number of deaths per day			
0.08		0.5				
0.17		0.3				
0.29		1.3				
Neoplasm deaths due to average SO_2 ppm (tertiles):	5		Average number of deaths per day			
0.08		7.4				
0.17		5.9				
0.29		9.6				
Total mortality rate	6	0.53	% reduction			Due to a 10% reduction in TSP in U.S. cities.

Appendix (Cont'd.)

Benefit categories	*Level of Information*								*Explanatory remarks*
	Qualitative benefit assessment	*Quantitative Benefit Assessment*							
		Reference	*Amount of benefit*	*Units of measure*	*Range of benefit uncertainty*	*$ value*	*Range of $ uncertainty*		
	Total mortality rate	6	0.37	% reduction					Due to a 10% reduction in smallest biweekly reading of sulfates. The t statistics for a test of zero effect of an increase in TSP and sulfates are respectively 2.53 and 3.18.
	1 $\mu g/m^3$ reduction in annual average particulate for: control diseases respiratory diseases circulatory diseases	7	 0.012 0.27 0.58	Reduced incidence of hospitalization					Large errors if extrapolate to total levels of SO_2 and TSP in the area (Pennsylvania).
	1 ppb reduction in annual average SO_2 for: control diseases respiratory diseases circulatory diseases	7	 -0.008 0.71 1.34	Reduced incidence of hospitalization					
	Respiratory diseases	7	3,000	Excess hospitalizations	254	1.92m	±0.162m		The uncertainty values are the standard errors. The average hospital cost per day was estimated to be $68.10 for respiratory disease, $67.20 for circulatory disease, and $71.30 for control diseases. Excess hospital costs were due to average SO_2 and TSP levels in Pennsylvania. See Ref. 7 for further data on hospital costs due to air pollution in Allegheny County. See Ref. 8 for morbidity benefits from aerosal acid sulfate abatement.
			28,205	Excess hospital days	2,386	0.625m	±0.163m		
	Circulatory diseases	7	5,640	Excess hospitalizations	838	5.19m	±0.771m		
			77,274	Excess hospital days	11,478	0.106m	±0.046m		

Control diseases	7	1,832	Excess hospitalizations	300	2.01m	±0.329m	
		28,214	Excess hospital days	4,615			
					9.85m		
Effect on the total mortality rate:	9		% Effect				The first three figures are cross sections and time series for a 50% reduction in annual average TSP and SO_4 levels; the last figure is for a 50% reduction in daily SO_2 levels in Chicago.
1960 (117 SMSAs)		4.7					
1969 (117 SMSAs)		5.8					
1960-69 (117 SMSAs)		4.5					
1965 (Chicago SMSA)		5.4					
Bronchitis	10(11)**	0.50	Coefficient attributable to air pollution		0.500b		Lave and Seskin's [Ref. 11] 1963 conservative estimates. Total includes annual cost of foregone earnings and current medical expenses due to mortality and morbidity benefits ascribed to a 50% reduction in all air pollution. A 100% reduction would yield a benefit of 0.7% of GNP, or $11.85 billion in 1976.
Other respiratory	10(11)	0.25			0.722b		
Lung cancer	10(11)	0.25			0.033b		
Other cancer	10(11)	0.15			0.357b		
Cardiovascular	10(11)	0.10			0.468b		
					2.08b		
Excess deaths per 100 $\mu g SO_2/m^3$	12	0.17	%				Cautions that the relationship is not very consistent.
Respiratory mortality	13(14)				1.9-2.2b		Social saving due to a 50% reduction in all air pollution (See Ref. 14)
Total mortality	13				886.6m		Total mortality benefits of reducing annual average SO_2 levels from an average for 40 SMSAs of 47.95 $\mu g/m^3$ to a threshold of 25 $\mu g/m^3$. Damages are in the form of foregone discounted future earnings (4% discount rate), in 1970 dollars. The computed partial elasticity of the average mortality benefits in the 40 SMSAs with respect to SO_2 level = 1.45. See Ref. 13 for the elasticity formula.

Appendix (Cont'd.)

Benefit categories	*Level of Information*							*Explanatory remarks*
	Qualitative benefit assessment	*Quantitative Benefit Assessment*						
		Reference	*Amount of benefit*	*Units of measure*	*Range of benefit uncertainty*	*$ value*	*Range of $ uncertainty*	
	Total morbidity	13				98.63m		Total morbidity benefits of reducing annual average SO_2 levels from an average for 40 SMSAs of 47.95 $\mu g/m^3$ to a threshold of 25 $\mu g/m^3$ (1970 dollars). These benefits represent direct (physician, drug, and hospital) costs and indirect (foregone earnings and leisure opportunity) costs. This figure is a "low" estimate, relying on conservative assumptions, and should more reasonably be five times its value. The partial elasticity of morbidity benefits with respect to SO_2 is 1.27. See Ref. 13 for mortality and morbidity benefit estimates from reduction in particulate levels.
	Residual mortality	15	0.00339	% increase in mortality				Benefit due to a 1 $\mu g/m^3$ drop in the sulfur dioxide level, obtained by constructing dose-effect functions. See Ref. 15 for threshold estimates for mortality and morbidity.
	Total morbidity and mortality	11	4.5	%				Savings of all economic costs associated with morbidity and mortality due to a 50% reduction in air pollution in major urban areas.

	Total morbidity and mortality due to:	2						Total air pollution includes sulfur oxides, particulates, and oxides.
	Sulfur oxides					1.9b	±1.2b	
	Total air pollution					4.6b	±3.0b	
	Total morbidity and mortality due to:	10						National estimates, 1968.
	Sulfur oxides					3.272b		
	Particulates					2.788b		
	Oxidants					–		
	Nitrogen oxides					–		
	All air pollution					6.06b		
Materials	All materials	1				1.4m 5.2m		Benefits due to a 1 $\mu g/m^3$ reduction in, respectively, ambient sulfur dioxide and sulfate levels in metropolitan New York. The authors caution that these are *"extremely crude estimates."*
	32 materials categories	2(16)				3.8b 2.2b	±.9b	The first figure is Salmon's [Ref. 16] "approximate" national estimate of the benefits of lessened materials corrosion from elimination of all air pollution. The second is a more "realistic" figure (p. 91). The results: (1) are subject to the substitution problem, (2) represent only 40% of all materials subjected to air pollution, and (3) are due mostly to particulates.
	Susceptible metal products	8(17)				1450m		The first is Fink, et al.'s [Ref. 17] national estimate of benefits from all air pollution abatement (primarily sulfur oxides). The second is *Spence and Haynie's* [Ref. 18] figure for particulates and sulfur oxides. The last is Gillette's [Ref. 19] estimate of sulfur oxides' effects on specific materials.
	Paints	8(18)				704m		
	Metals and paints	8(19)				400m		

Appendix (Cont'd.)

Benefit categories	Level of Information							Explanatory remarks
		Quantitative Benefit Assessment						
	Qualitative benefit assessment	*Reference*	*Amount of benefit*	*Units of measure*	*Range of benefit uncertainty*	*$ value*	*Range of $ uncertainty*	
	All materials	10				4.752b		All figures are national estimates (except where indicated) of the materials benefits from 100% abatement of all air pollution.
	Metal corrosion	10(20)				5.4b		
	Metal corrosion	10(21)				7.5b		
	Painting	10(22)				0.15b		
	Electrical contacts	10(23)				0.065b		
	53 material types	10(16)				3.8b		
	Steel corrosion	10(24)				4.5b	+8.5b -3.1b	
	Textiles and fibers	10(25) 10(26)				2.0b		
	Rubber	10(27)				0.38b		
	Soiling (1970)	13				5.033b 0.516b		The first figure is total soiling benefits from following TSP abatement in 148 SMSAs; the second is the same for the Chicago SMSA. The estimates are a composite of nine cleaning tasks and their assigned unit market values, ranging from $0.50 for washing an inside window to $15.00 for cleaning gutters. Zinc and Paint benefits account for over half of the benefits to 53 economically significant materials studied by Salmon [Ref. 16]. The figures are rather high due to the stringent assumption that the materials would be maintained completely clean at all times.
	Soiling of Zinc:	13						
	National					24b		
	148 SMSAs					15.12b		
	Deterioration of Zinc:	13						
	National					0.778b		
	148 SMSAs					0.496b		
	Soiling of Paint:	13						
	National					35b		
	148 SMSAs					22b		
	Deterioration of Paint:	13						
	National					1.2b		
	148 SMSAs					0.753b		

Zinc corrosion rate	15(28)	4	four-fold reduction in rate				Yocum's [Ref. 28] estimate in Pittsburgh due to a drop in annual average SO_2 concentration from 390 to 130 $\mu g/m^3$ over a 34-year period.
Corrosion rate of mold low-carbon steel	15(29)	50	% rise in rate				Due to rise in SO_2 concentration from 80 to 315 $\mu g/m^3$ in Chicago. Upham [Ref. 29] found this to be a linear relationship.
53 materials	15				3.8b		The first figure is from Salmon's list of the 53 most economically significant materials, making up 40% of all materials subject to air pollution. The second is his estimate assuming all materials are subject to damage functions similar to those studied. The following list represents the 19 materials studied by Salmon which are most "susceptible to deterioration by sulfur oxides."
All materials	15				9.5b		
Paint	15				1195m		
Zinc	15				778m		
Nickel	15				260m		
Tin	15				144m		
Carbon steel	15				53.8m		
Brass and bronze	15				13.4m		
Magnesium	15				13.0m		
Alloy steel	15				8.7m		
Bituminous steel	15				2.2m		
Gray iron	15				1.9m		
Clay pipe	15				1.4m		
Malleable iron	15				0.9m		
Chromium	15				0.8m		
Silver	15				0.7m		
Gold	15				0.6m		
Glass	15				0.3m		
Molybdenum	15				0.1m		
Refractory ceramics	15				0.02m		
Carbon and graphite	15				0.003m		
					2470m		
Exterior paints	15(18)				700m		Spence and Haynie's [Ref. 18] estimate of annual benefits from abatement of ozone, SO_2, particulates, and hydrogen sulfide. Nearly 75% of this figure was due to effects on household paints.

Appendix (Cont'd.)

Benefit categories	Level of Information: Qualitative benefit assessment	Quantitative Benefit Assessment: Reference	Amount of benefit	Units of measure	Range of benefit uncertainty	$ value	Range of $ uncertainty	Explanatory remarks
	Corrosion	15(17)				1.45b		Fink, et al.'s [Ref. 17] estimate of corrosion benefits for each of nine categories of metallic systems in the form of reduced maintenance expenses and augmented service life. More than 90% was accounted for by zinc corrosion, with SO_2 being the most important pollutant.
	All materials	15(2)				600m	±200m	Waddell's [Ref. 21] national estimate of benefits due to sulfur oxide abatement, derived from several reports.
	All materials	15				14.75 10.82 4m	±2.00 ±1.50 +16m -3m	The first figure is the annual per capita benefits from sulfur oxide abatement for urban areas. The second is the same for the entire U.S. The third is the best estimate of annual benefits for Illinois of a reduction in sulfur dioxide of 1 $\mu g/m^3$ per year.
	All materials, due to: Sulfur oxides Total air pollution	2				 0.6b 1.7b	 ±0.2b ±0.7b	Total air pollutants include sulfur oxides, particulates, and oxides.
	All materials, due to: Sulfur oxides Particulates Oxidants Nitrogen oxides Total air pollution	2				 2.202b 0.691b 1.127b 0.732b 4.752b		National estimates, 1968.

Vegetation	Crop losses	2				3.3m		Due to sulfur dioxide. SRI ignored recreation areas (ornamentals), loss resulting from reduction in yield, grower relocation, crop substitution, loss in productivity, and denudation of land.
	Ornamental losses	2				3.0m		
	All vegetation	2				Negligible	—	Waddell's estimate of losses due to sulfur oxides and, secondly, sulfur oxides, particulates, and oxides.
						0.2b	±0.1b	
	Direct agricultural losses	10				3.5m		Due to all air pollution in Pennsylvania (1969). Pollutants in order of decreasing importance: oxidants, sulfur oxides, lead, hydrogen chloride, particulates, herbicides, ethylene. Vegetation affected, in order of decreasing importance: vegetables, fruits, agronomic crops, lawns, shrubs, woody ornamentals, timber, and commercial flowers.
	Indirect agricultural losses:	10						
	Profit losses					7.0m		
	Reforestation					0.5m		
	Grower relocation					0.5m		
						11.5m		
	All vegetation except home plantings and flowers due to:	10(30) (31)						SRI national study of air pollution effects on yield, quality, and marketability (see Refs. 30, 31).
	Hydrocarbons					64m		
	Sulfur oxides					4m		
	Fluorides					2m		
	Other					10m		
	All vegetation	10				120m		National estimate due to all air pollutants for 1968.
	All vegetation	13				58.46m		1970 estimate. Only 74 counties of 679 studied had both positive crop loss estimates and data on climate and pollution levels. The partial elasticity of all plant damage with respect to sulfur dioxide = 0.18.

Appendix (Cont'd.)

Benefit categories	Level of Information							Explanatory remarks
	Qualitative benefit assessment	Quantitative Benefit Assessment						
		Reference	Amount of benefit	Units of measure	Range of benefit uncertainty	$ value	Range of $ uncertainty	
	Total crops Ornamentals All plants	13 13 13				0.149m 0.766m 0.888m		Damages in Cook County, Ill. (1970).
Property Value	Residential marginal capitalized damage	2(32)				470		Crocker's [Ref. 32] Chicago estimate of the mean change in median residential property value per change of 0.001 ppm SO_2/72 hrs. plus 10 $\mu g/m^3$ daily change in suspended particulates. See Ref. 2 for regression coefficients.
	Residential marginal capitalized damage	10(33) (34) (35) (36)				200 5.2b	±100	The first figure is the change in marginal capitalized residential value for a 0.1 mg SO_3/100 cm^2/day change. This translates into the second figure, the national damages due to SO_3 in all SMSAs above 0.1 mg SO_3/100 cm^2/day. Barrett and Waddell used information from Refs. 33, 34, 35, and 36.
	Owner-occupied housing value Rental housing (monthly rent).	34 34(37) (38)				500 3	±200 ±1	Marginal benefit due to a reduction in suspended particulates of 10 $\mu g/m^3$ and 0.1 mg SO_3/100 cm^2/day. OLS method used to generate values for three dependent variables: (1) median property value, (2) median gross rent, and (3) median contract rent. See Refs. 37 and 38 for interesting discussions of the worth of property value estimates.

	Residential value	35				966	+834 -166	Increase in property values due to a 1 mg SO_3/100 cm^2/day change.
	Single family dwellings	39				164	±81	Change in single family dwelling value due to a 0.25 mg SO_3/100 cm^2/day change. The authors feel the upper limit (245) is best.
	Residential property	32				450		Average marginal capitalized change in property values due to a 10 $\mu g/m^3$ change in suspended particulates and a 1 ppb change in SO_2 for a 24-hour period in Chicago (1964-67).
Ecological	Ecosystems damage by acid rain	1				0.015		Figure is a crude national estimate of ecological damage per pound of sulfur emitted.
Aesthetics	Aesthetics	1				0.034		Crude national estimate of aesthetic damages per pound of sulfur emitted.
	Aesthetics and soiling due to: Sulfur oxides Total air pollution	2				 2.9b 5.8b	 ±1.2 ±2.4	Total air pollution includes sulfur oxides, particulates, and oxides.
Animal Health	Control of pulmonary flow resistance in guinea pigs	40	+3.5 -5.5 +45	% change				Figures are for 2-hour exposures to (top to bottom): 1-1.2 ppm SO_2, 900-1000 μg aerosol/m^3, and a combination of the above. The 45% figure indicates a synergistic effect involving SO_2 and aerosol (NaCl).
Total Benefits	Waddell (base year = 1970)	2				12.3b	±6.2b	These are national estimates for the total benefits from a 100% reduction in air pollution. Most are a synthesis of the separate categories presented above.
	Ridker (base year = 1970)	8(41)				7.3-8.9b		
	Gerhardt (base year = 1968)	8(42)				8.1b	+7.1b -2.1b	
	Barrett and Waddell (base year = 1968)	10				16.1b		
	Justice et al. (base year = 1970)	8(43)				2-8.7b		

Appendix (Cont'd.)

Benefit categories	*Level of Information*							*Explanatory remarks*
		Quantitative Benefit Assessment						
	Qualitative benefit assessment	*Reference*	*Amount of benefit*	*Units of measure*	*Range of benefit uncertainty*	*$ value*	*Range of $ uncertainty*	
	Babcock and Nagda (base year = 1968)	8(44)				20.2b		
	National Academy of Sciences (base year = 1973)	8(45)				20b	+10b -5b	
	Heintz and Hershaft (base year = 1973)	8(46)				20.2b	+15.2b -10.7b	
	Equitable Environmental Health	15				0.225b	±0.075b	Figure is all benefits to the residents of Illinois from a reduction of 1 $\mu g\ SO_2/m^3$ per year. However, they attribute no benefits to health and vegetation, and all to materials benefits.
	General							See Refs. 3, 4, 7, 15, and 47 for useful information on threshold estimates for health and vegetation benefits.

* m = million, b = billion.
** Reference numbers in parentheses indicate that the primary reference used or cited the parenthetical reference.

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