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SEASONAL ANALYSIS

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Copper Smelters and Atmospheric Visibility in the
Southwest, Seasonal Analysis

by

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Introduction

This paper presents the results of the seasonal analysis from a study which has evaluated the effects of copper smelter emissions on atmospheric visibility in southwestern national parks and wilderness areas. The study also examined these effects on an episodic basis and conducted statistical analyses of aerosol and visibility measurement data before and during the summer 1980 copper strike. The latter results are presented in the final report.¹

Excellent visibility, frequently approaching pristine levels, are experienced in many of the southwestern national parks and wilderness areas. Congress, under the 1977 amendments to the Clean Air Act, established as a national goal the protection of visibility from impairment in these and other areas. Sulfur dioxide (SO_2), through chemical reactions in the atmosphere, is converted to sulfates (SO_4), which are very effective light scatterers per unit mass. Past studies have shown that SO_4 , which can be transported in air masses over long distances, is a major contributor to visibility reduction in the Southwest.²⁻⁸ Copper smelters have been the major emitters of sulfur oxides (SO_x) in the Southwest. They contributed to over 70% of the SO_x emitted in the Four Corners states in 1975.^{9,10} The contribution of the copper smelters to visibility reduction versus all other contributions, natural as well as anthropogenic, is estimated at selected locations.

Control Strategies

The EPA initiated this study to evaluate the effectiveness of the constant emission control (CEC) strategy in improving visibility at southwestern national parks and wilderness areas. The southwestern states of Arizona, Nevada, New Mexico, and Utah are implementing the CEC strategy to control SO_x emissions from copper smelters as part of their state implementation plans (SIP). The SO_x emissions are being controlled not for the purpose of improving visibility but in order to meet National Ambient Air Quality Standards (NAAQS) for SO_2 in the vicinity of the smelters. Controlling SO_x emissions has the added benefit of improving visibility. All but 2 of the smelters in the study have been using supplementary control systems (SCS) to reduce NAAQS violations for SO_2 . SCS reduces SO_x emissions during adverse meteorological conditions through production curtailment.

The SCS control alternative is based on actual copper smelter SO_x emissions and operating conditions during the year 1979. The year 1979 was selected because it is fairly representative of production levels, though highly variable, from 1965 to 1978 and of copper smelter SO_x emissions for the latter half of the 1970s (see Tables I and II). In more recent years, the production levels have been down and the copper industry is currently in an economic depression with many of the smelters and mines either shut down or operating at reduced capacity. The low production has been caused partly by an industry-wide strike in the summer of 1980 and a weak demand for copper resulting from a world-wide recession and policies of foreign copper producing countries.

Table I shows significant improvement in smelter SO_x control from 1970 to 1975 and from 1975 to 1979. Under the CEC control alternative, it was

estimated that the smelter SO_x emissions would be further reduced to one-third the level under the SCS control alternative. The CEC control alternative SO_x emissions are based on 1979 smelter production rates and on the emission limits proposed by four of the southwestern states.

Copper Smelters

The 11 southwestern copper smelters included in this study are listed in Table III and are shown in Figure 1. The ASARCO smelter in El Paso, Texas was not included in this study because it could not be determined at this time what its emissions would be under the CEC control alternative. Exclusion of this smelter from this study may, to some extent, causes an understatement of the visibility improvement associated with the change from the SCS to the CEC control alternative. The magnitude of this effect is probably small and is related to the magnitude of the CEC-related reduction of the SO_x emissions from the El Paso smelter. As of 1975, the El Paso smelter emitted less than 3% of the total southwestern copper smelter SO_x emissions.⁹ The magnitude of the effect would also likely be more important for the southernmost parks and wilderness areas in this study, particularly the two areas located in Texas.

National Parks and Wilderness Areas

The effect of the copper-smelter generated SO_4 on atmospheric visibility reduction was estimated for 14 southwestern national parks and wilderness areas (see Figure 2). These areas are given special protection against visibility impairment under Sec. 169A of the 1977 Amendments to the Clean Air Act and as specified by EPA's visibility rules.¹¹ The visibility impacts were evaluated on both a seasonal and on an episodic basis.

Air Pollution Regulations

The laws and regulations that are relevant to the two alternative regulatory policies being examined to control sulfur oxides are discussed. Current Federal legislation allows copper smelters under certain circumstances to employ SCS as an interim measure but requires them to meet continuous emission limits by January 1, 1988. Currently, 9 of the 11 copper smelters in this study (all except the Kennecott smelter at Hayden, AZ and the Phelps Dodge smelter at Hidalgo, NM), to varying extents, are using SCS. Under Section 119 [Primary Nonferrous Smelter Order (NSO)] of the Clean Air Act, as amended in 1977, a copper smelter is allowed to use interim controls, such as SCS, if it can show that the use of continuous emission control would cause undue economic hardship. The copper industry is requesting Congress to extend the NSO provision. Due to legal complications attendant with EPA's NSO program, no NSO's have been granted thus far. On July 30, 1982, the D. C. Circuit Court of Appeals vacated EPA's NSO regulations and remanded them to EPA for further action. The applications of Kennecott's smelters at McGill, Nevada and Hurley, New Mexico; Magma's smelter at San Manuel, Arizona; and Phelps Dodge smelter at Douglas, Arizona are pending the resolution of the problem.

Under the Clean Air Act of 1970, the states are required to set emission limits for the copper smelters. These emission limits when approved by EPA become part of each state's SIP. The states of Arizona, Nevada, New Mexico, and Utah have proposed new emission limits for their copper smelters and have submitted them to EPA as revisions to their SIPs. The Arizona and New Mexico SIP revisions have recently been approved by EPA. New Mexico had proposed a new emission limit only for the Kennecott smelter. The other New Mexico smelter owned and operated by Phelps Dodge already had an approved emission limit of 90% continuous control. This smelter is allowed to run at a lesser control level during upset conditions.

The proposed emission limits are of a new type and are called multipoint rollback (MPR) emission limits. Instead of specifying a single limit not to be exceeded (single-point rollback), they specify an annual average and a frequency distribution of limits not to be exceeded. The proposed annual average emission limits are shown in Table IV. The MPR approach is a probabilistic approach that allows high emissions to occur for a small frequency of the time. They are designed such that the NAAQS for SO₂ of short duration (less than or equal to 24 hours) are not to be exceeded more than once per year in the expectation. The advantage of MPR compared to single-point rollback, is that it reduces the importance of the relatively low joint probability occurrence of worst case meteorology and plant emissions, with the effect of easing the pollution control burden. Experience will be needed to see whether the proposed limits will be successful on the average in meeting the NAAQS for SO₂.

The MPR limits were derived under the assumption that the frequency distribution for stack emissions and the meteorological related parameter relating emissions to ground level concentration were independent. The data used to estimate the MPR limits was from the period the smelters were employing SCS. These data were empirically corrected for SCS contamination. The MPR limits apply only to stack emissions. The smelters are being required to also reduce their fugitive SO_x emissions when they are indicated to be contributing to the violation of NAAQS.

The two alternative regulatory policies are both required to meet NAAQS for SO₂. SCS has been used for several years by the southwestern smelters. SCS has not been successful at eliminating violations. The number of SO₂ standard violations for the Arizona smelters are shown in Table V.

Methodology

The methods used in calculating the atmospheric visibility effects caused by the smelter SO₄ for each of the two control alternatives are presented in this section. The regional transport model (RTM) and the approach used for calibrating the model is discussed. The method used to relate SO₄ aerosol concentration to visual range is described. Human perception of the impairment of atmospheric visibility is defined.

Regional Transport Model

A two-dimensional Eulerian air pollutant transport model was used to estimate the concentration of particulate sulfates (SO₄) on a seasonal

average basis. The model accounts for the atmospheric processes of advective transport, transformation, dispersion, and wet and dry deposition.^{12,13} The outputs from this model were used as inputs to the atmospheric visibility calculations. The concentrations were estimated for 2° by 2° grid cells that extend vertically to the top of the mixing layer and that extend from 26° to 46° latitude and from 98° to 120° longitude (see Figure 3). A more detailed description of the seasonal RTM is found in the Appendix.

One major advantage of the transport model employed is that its solution involves the calculation of transfer coefficients that relate air pollutant emissions directly to ambient concentrations. The transfer coefficients can be derived mathematically as follows.

$$X_j = \sum_i t_{ij} E_{ij} \quad (1)$$

where: X_j = concentration in cell j.

E_i = emissions in cell i.

t_{ij} = the transfer coefficient which relates the emissions in cell i to the concentration in cell j.

The transfer coefficients need to be calculated only once for a given time period and set of model parameters. They can be used repeatedly for the analysis of alternative regulatory policies with different emission source configurations.

The RTM has undergone testing. For the southwest, the model was tested using results from a study by Mariani and Trijonis.¹⁴ This study analyzed the historical effects of SO_x emissions from copper smelters on observed visibility and SO_4 concentrations. They estimated a proportionality coefficient between extinction and smelter SO_x emissions based on both airport visibility data and National Air Surveillance Network (NASN) SO_4 data.

A proportionality coefficient between SO_4 concentration and SO_x emissions can be directly related to the extinction/emissions coefficient. Their estimated SO_4 /emission coefficient ranges between 0.25 to 0.75 ($\mu g/m^3$)/(1000 tpd SO_x) at distances of 50 to 200 miles from the sources. This coefficient was estimated using a light scattering to mass ratio of 0.004 $km^{-1}/(\mu g/m^3)$ to convert extinction into SO_4 concentration.¹⁴ Based on the RTM modeling results from a study done for the National Commission on Air Quality (NCAQ), a SO_4 /emissions coefficient of 0.497 ($\mu g/m^3$)/(1000 tpd SO_x) was estimated with a correlation between SO_4 concentration and study region SO_x emissions of 0.9995.² The estimated coefficient corresponds to an average area weighted pollutant transport distance of about 190 miles. The SO_4 /emissions coefficient based on the RTM results is within the range of values based on the results from the Mariani and Trijonis study.¹⁴

Calibration of the Regional Transport Model

The RTM was calibrated to the southwestern copper smelters. The calibration was done for the 4 seasons of 1979. The RTM was calibrated against a historical relationship between the southwestern copper smelters' SO_x emissions and extinction and SO_4 concentration using actual 1979 copper smelter SO_x emissions. The historical relationship was estimated by Marians and Trijonis based on data during and surrounding the 9-month 1967-1968 copper strike.¹⁴ Using an extinction to mass concentration ratio of $0.004 \text{ km}^{-1}/(\mu\text{g}/\text{m}^3)$ for SO_4 , gives the following relationship versus distance (d) of copper smelter SO_x emissions (E) in 1000 tpd and SO_4 in $\mu\text{g}/\text{m}^3$:

$$\text{SO}_4 = 41.5 \text{ E}d^{-0.95} \quad (2)$$

The correlation between the logs of SO_4/E and distance for this empirical historical relationship was -0.83, which indicates a good agreement between SO_4/E and distance. The historical relationship does not give seasonal estimates. Seasonal estimates were obtained by adjusting the historical relationship's estimates according to the copper smelters' contribution to the 1979 observed seasonal sulfate concentrations at NASN sites.¹

In the RTM calibration, the model parameter representing the first order chemical conversion rate of SO_2 to SO_4 was allowed to vary. The deposition rate parameters were held constant during the calibration (see Table VI). The calibrated conversion rates are compared in Table VII to conversion rates based on smelter and power plant plume field measurements analyzed by Eatough et al.^{15,16} The calibrated conversion rates and the ones based on field measurements show good agreement except for the summer season. The calibrated conversion rates are higher in the spring and summer, near 1% per hour, than in the fall and winter, about 0.5% per hour.

Plume conversion rates from field measurements were fitted by Eatough et al. versus temperature to the Arrhenius equation.^{15,16} The best fit Arrhenius equation gave an apparent activation energy of $16.6 \pm 1.4 \text{ kcal mole}^{-1}$ with a correlation of 0.909. The conversion rates based on field measurements that were compared to the calibrated conversion rates were calculated using the fitted Arrhenius equation and seasonal temperatures averaged through the mixing layer at Winslow, Arizona.

The model was calibrated for 11 grid cells containing the 14 southwestern national parks and wilderness areas being studied. The model was calibrated such that its and the historical relationship's mean SO_4 concentration over the 11 cells would agree to within 5%. A plot of the RTM SO_4 concentration estimates versus the historical relationship estimates for winter season is shown in Figure 4. Very good agreement is found between the two estimates. Quantitative measures (mean, standard deviation, mean squared difference, and the correlation coefficient) that provide a comparison of the agreement between RTM and the historical relationship are found in Table VIII. These quantitative measures show very good agreement between the two. One of the major reasons for differences may be because the historical relationship does

not account for the effect of wind direction in transporting the smelter plumes.

Relationship Between Aerosol Concentration and Visual Range

In this section, the methods used for calculating visibility at the 14 national parks and wilderness areas in the study are discussed. Two visibility parameters are calculated, the light extinction coefficient, b (in km^{-1}), and the visual range, V (in kilometers). The light extinction coefficient due to light scattering by sulfates generated by the smelter sources is calculated for each of the areas. Visual range is calculated for the areas with, or which are nearby, the Visibility Investigative Experiment in the West (VIEW) network monitoring sites.^{17,18} The VIEW sites at Canyonlands and Carlsbad were used as the nearby sites for Arches and Guadalupe, respectively. In the visual range calculations, the contributions of the smelters and all other sources are estimated.

Through a relationship proposed by Koschmieder, visual range for black objects can be related to the extinction coefficient defined in the Beer-Lambert Law.¹⁹ The relationship has also been found to be a good approximation for calculating the visual range of dark topographical features, such as forest-covered mountains. The relationship for the "limiting distinguishable contrast" of the black object against the horizon sky for a standard observer is given by

$$V = 3.9/b \quad (3)$$

V is known as the "meteorological visual range." The value used for the limiting distinguishable contrast for the standard observer is 0.02.¹⁹

The extinction coefficient can be represented by the sum of the following components:²⁰ the light-scattering coefficient caused by atmospheric particulates, b_{sp} ; the light-scattering coefficient caused by air molecules (Rayleigh scattering), b_{sg} ; the light absorption coefficient caused by gases such as NO_2 , b_{ag} ; and the light absorption caused by particles such as carbon-black, b_{ap} . The relationship can be represented as

$$b = b_{sp} + b_{sg} + b_{ag} + b_{ap} \quad (4)$$

The total light extinction, b_T , at each national park or wilderness area is calculated as the sum of the following three components: (1) the light scattering caused by air molecules, b_{sg} ; (2) the light scattering caused by the sulfates generated by the smelter sources, b_{ss} ; and (3) the extinction caused by all other sources, b_{eo} . The equation used for calculation of the total light extinction coefficient, b_T , is expressed as

$$b_T = b_{sg} + b_{ss} + b_{eo} \quad (5)$$

The light scattering by the smelter sulfates is estimated as the product of the scattering to mass ratio for sulfates, $(b_s/m)SO_4$, in units of $(km^{-1}/(\mu g/m^3))$, and the concentration of the sulfates, $[SO_4]$, estimated by the regional transport model.

$$b_{ss} = (b_s/m)SO_4 * [SO_4] . \quad (6)$$

Sulfate particles are found in the size range comparable to the wavelength of light, 0.1-1 microns in radius.²¹ Particles found in this size range are the most effective light scatterers per unit mass.²² Sulfates are hygroscopic particles that will grow in size with increasing relative humidity. The particle growth will cause the scattering-to-mass ratio to increase. Based on both theoretical calculations and empirical estimates from observed data, the scattering to mass ratio for sulfates can be estimated as a function of percent relative humidity, RH, through the following relationship:^{5,23,24}

$$(b_s/m)SO_4 = 0.0024/(1 - RH/100) . \quad (7)$$

The extinction caused by all other sources was estimated for the 1979 episodic and seasonal periods. It was estimated for the areas with or nearby VIEW network monitoring sites by subtracting from the total light extinction the Rayleigh scattering and the extinction estimated to be caused by the smelters. The total light extinction was estimated from 1979 visual range data from the VIEW network monitoring sites using Eq. (2). The extinction caused by the smelters was estimated from the RTM sulfate concentration estimates and the relative humidity data using Eqs. (5) and (6).

Perception of Visibility Effects

The human eye-brain system identifies objects through perception of contrast or motion. In the context of visibility, alterations of a scene are associated with altered patterns of contrast. The best way to represent a scene is with a picture that can supply the myriad of contrast elements normally found in an actual scene.²⁵ Furthermore, the eye-brain system's response to contrast is dependent upon the spatial scale of the difference between brightness in various parts of the scene. Very slow changes in brightness are not readily perceived, while abrupt changes associated with edges of different materials are readily perceived. Once again, a picture is a superior method of presenting visibility effects.

In many circumstances, simpler methods of estimating visibility impacts are useful. In a past study, Trijonis attempted to give estimates of thresholds of perception for contrast based on information from a literature review.²⁶ The estimates were given for the case of the observer embedded in a plume or haze layer, Case A, and the case where the observer is outside of the plume or haze layer and viewing the haze against a cleaner background, Case B. The plume or haze is expected to be more perceptible in Case B where

there is a simultaneous comparison of the plume or haze against the background. Trijonis also related the change in contrast (ΔC) to a corresponding change in visual range. This relationship depends on the distance to the skyline terrain features in the scene being considered. The estimate of the contrast thresholds and the corresponding estimated perceptible change in visual range are presented in Table IX. Two values of the latter are given, one at the point of maximal impact and a second for an average contrast change integrated over the visual range. It should be emphasized that currently there is not consensus concerning acceptable thresholds of perception and that the ones discussed are inadequate for addressing the discoloration problem.

Data

Several different sets of information were required to be collected for this study. A major effort was made to collect the data used in this study. State and Federal agencies and the copper smelters were contacted for information. Visits were made to the Arizona, New Mexico, and Utah Bureaus of Air Quality Control in order to obtain information that were available from their files. The information gathered ranges from that concerning copper smelter unit processes to visibility data. A discussion of the smelters' unit processes and the SO_x emissions under the two control alternatives are presented. The meteorological data used as input to the regional transport model and the visibility calculations are described. The visibility data were used in estimating the contribution to the total extra light extinction by smelter and non-smelter sources, natural as well as anthropogenic.

Unit Processes

The control of the sulfur oxide byproduct found in the off gases produced in the smelting of copper concentrates is determined to a large extent by the unit processes used in the smelting. All of the southwestern copper smelters pyrometallurgically process copper concentrates. The steps in the pyrometallurgical processing are illustrated in Figure 5. There is a variety of specific unit processes that can be used at each step, and some unit processes combine steps.

The efficiency and the cost of removing the byproduct SO_x from a process' off gases depend on the volume of gas being treated and on the SO_x volumetric concentration in the off gases. Off gases from processes with strong SO_x concentrations (greater than 4%) can be treated in sulfuric acid plants without requiring reheat. There are a variety of processes, many in the demonstration stage or that have become commercially available in the past few years, that can treat dilute concentrations (less than 2%), though at significantly higher cost per unit removed than for an acid plant. Many of the smelters in the early 1970s added acid plants to treat the off gas streams with strong SO_x concentrations. More recently, many of the smelters have been moving towards modifying or replacing processes which produce off gases having dilute SO_x concentrations to those which produce off gases with strong SO_x concentrations. These strong off gases can be treated in sulfuric acid plants.

The specific unit processes for the smelters which existed in 1979 and which are expected in the future are listed in Table X. Most of the smelters currently do not use roasters, but use reverberatory furnaces, Pierce-Smith converters, and single- or double-contact acid plants. Off gases from fluid bed roasters and converters are sufficiently concentrated in SO_x so that they can be treated by an acid plant, while off gases from reverberatory furnaces are not and cannot be effectively treated by an acid plant. Reverberatory furnaces at most of the smelters have been, are planned to be, or are under consideration to be replaced by newer furnace technologies, such as flash, Noranda, oxygen sprinkle, or electric. All of these technologies produce off gases that can be treated by a sulfuric acid plant. Economic considerations will determine the viability of each smelter and whether or not these process modifications are feasible.

A smelter treating off gases from a tightly hooded converter in an acid plant can expect approximately 55% or 57-58% overall SO_x control, for single- or double-contact acid plants, respectively. With the addition of a roaster and with the roaster gases going into an acid plant, one can expect approximately 70% overall SO_x control. For a modern smelter with the off gases from both tightly hooded converters and one of the new technology furnaces being treated in an acid plant, one can expect 85 to over 90% control. More detailed discussions of smelter unit processes and SO_x control can be found elsewhere.^{9,27}

Sulfur Oxide Emissions

The SO_x emissions on a seasonal basis for both 1979 and the CEC alternative are shown in Table XI. These emissions are used as input to the seasonal regional transport model. The 1979 emissions are actual reported emissions and reflect the use of SCS. The CEC emissions were developed using the same production rates as occurred in 1979 and assuming the smelters would be at SO_x emission control levels that would meet the CEC limits. The seasonal 1979 production rates, expressed as tpd of input sulfur, are presented in Table XII.

The SO_x emissions were partitioned into SO_2 and primary SO_4 (SO_3 and particulate SO_4) emissions. Plume samples taken within a few kilometers of smelter stacks indicated that about 1-4% of the SO_x emissions, on a molar basis, were in the form of primary SO_4 and the remainder were in the form of SO_2 .^{9,14} For the regional transport model calculations, a value within this range of 2% was used as the mole fraction for the SO_x emitted as primary SO_4 .

Meteorological Data

The meteorological data which were used as input to the RTM and the visibility calculations are described in this section. Seasonal, climatological mixing heights, precipitation, and 800-mb average directional winds were the meteorological inputs to the seasonal RTM. The meteorological parameters were supplied for the RTM grid system that extends from northern New Mexico to southern Wyoming and from Kansas to eastern California (see Figure 3). An average mixing height was estimated for each season. The

mixing height limits the vertical extent of mixing for a plume trapped within the mixing layer. The mixing heights varied seasonally with the higher values of 1540 and 1620 meters estimated for the spring and summer seasons, respectively, and the lower values of 740 and 870 meters estimated for the winter and fall seasons, respectively. The estimated mixing heights were based on data reported by Holzworth.²⁸

Precipitation rates were supplied for each of the 110 2 by 2 degree grid cells that comprise the RTM grid system. The precipitation rates are used in the RTM model as input to wet deposition rate calculations. The region modeled is arid with average precipitation rates ranging from about 10 to 25 inches per year. The precipitation rates used are averages over a 5-year period, 1966-1970, and are based on data reported by the National Weather Service.²⁹ The relative humidity data were used in the visibility calculations (see Table XIII). These data are interpolated values based on climatological data from southwestern weather stations.³⁰

The 800-mb upper air average directional winds were estimated for each of the 110 grid cells. The 800-mb level winds were used because they are believed to be the level most representative of the steering winds in the mountainous west for regional scale advective transport. The magnitude of the average wind components were estimated to be generally larger in the spring and particularly in the winter season as compared to the summer and fall seasons. Generally, the westerly and southerly average wind components were found to be larger than the easterly and the northerly components. The two-dimensional seasonal wind fields were based on data prepared by Crutcher.³¹

Visibility Data

Historical visibility data were used in the visibility calculations as already discussed in the methodology section of this paper. The visibility data comes from the VIEW monitoring network which has been funded by the EPA and the National Park Service.^{17,18} A manual telephotometer is used in the network to measure the light intensities of distant targets and the background sky. Typically, the instruments are operated by park personnel and the measurements are made 3 times per day for as many as 5 lines of sight. Visual ranges can be calculated based on these light intensities and the distances to the target. The calculation is not as reliable during cloudy conditions or when the targets are snow covered. The data for these and adverse weather conditions were not used when computing seasonal visibility statistics. The monitoring sites used in the study included the ones located at the Grand Canyon, Bryce Canyon, Canyonlands, Carlsbad National Park, Bandelier National Monument, and Big Bend National Park. The median visual range by season for 1979 for these sites are reported in Table XIV.

Results and Discussion

In this section, the results from the seasonal comparison of the SCS versus the CEC control alternatives are presented. The results from the regional transport model and visibility calculations are presented in Tables XV - XVII. The results vary by season and location. The results show that

the CEC alternative could significantly improve visibility in 4-6 out of 8 of the national parks and wilderness areas and could substantially reduce the smelter contribution to sulfate concentration in all 14 areas. The smelters were found to be a significant contributor to visibility reduction in 7 out of 8 of the southwestern national parks and wilderness areas studied. Their relative impact on atmospheric visibility was found to be the greatest in the summer and fall when a high visitation to these areas occurs.

Four parameters were used in the comparison of the 2 control alternatives. They include the estimated sulfate concentration and the scattering coefficient (b_{scat}) caused by the smelter SO_x emissions, the estimated visual range, and the estimated percent of the total extra extinction caused by the smelter SO_x emissions. The total extra extinction accounts for both the anthropogenic and natural source contributions except for the light scattering by air molecules called Rayleigh scattering. The first two parameters were calculated for each of the study's 14 national parks and wilderness areas. The latter two parameters, in order to be calculated, required 1979 visibility data and could only be calculated for the 8 national parks and wilderness areas that had or were nearby VIEW network monitoring sites. The other 6 areas, 4 located in southern and central Arizona and 2 located in New Mexico, were not nearby the VIEW monitoring sites. The impact of the smelters SO_x emissions on atmospheric visibility should be largest for the 4 southern and central Arizona areas because they are closest to the highest concentration of smelter SO_x emissions. Therefore, the results for the 8 areas should be an understatement of the impact on these 4 areas. It should be kept in mind that some of the results, particularly for the two Texas areas and some of the other southernmost areas, may have been somewhat different if the El Paso smelter had been included in the study. The difference would have been in the direction of the CEC control alternative having an even larger related improvement in visibility.

Sulfate Concentration and Light Scattering

The striking difference between the SCS and the CEC control alternatives is that the SO_x emissions of the latter scenario are reduced to one-third of those of the former scenario. This difference has a striking effect on the SO_4 concentration and b_{scat} calculations with the magnitude of these parameters for the CEC control alternative generally being one-third of that for the SCS control alternative. The relative differences tend to be greater in the summer and smaller in the winter and for the Golden Circle areas. The magnitude of these parameters are generally higher for the Arizona and New Mexico areas and substantially lower for the two Texas areas. This effect is likely related to atmospheric flow patterns, which frequently have strong southerly and westerly components, and to the closer proximity of the Arizona areas and Gila Wilderness to the smelter sources. The difference in the magnitude of the two parameters between the Golden Circle and New Mexico areas decreases for the summer and fall seasons, particularly for the CEC alternative.

The SO_4 concentration and b_{scat} parameters are highest in the summer and fall and lowest in the winter except for the two Texas areas. The New Mexico areas also tend to have relatively higher values in the spring. The

relatively higher values in the summer and spring are related to the higher SO₂ to SO₄ transformation rate during these seasons. The relatively higher values in the summer are also related to the lower magnitude of the average directional transport wind components during this season. The relatively higher values in the fall are related to the lower magnitude of the average directional transport wind components and the lower mixing depth during this season. The relatively lower values in the winter are related to the lower transformation rate and the higher magnitude of the average directional transport wind components during this season. The two Texas areas have relatively higher values in the spring and fall, and their lowest values in the summer. The lowest values in summer are likely related to the higher easterly versus westerly average directional wind component for the southern portion of the modeling grid system during the summer.

Visual Range

The differences in visual range between the two alternatives for the eight areas depend on season and location. The regional visibility is better for the CEC alternative (0 to 28% higher) versus the SCS alternative. Except for the 2 Texas areas, the differences between the alternatives is largest for the summer and fall (13 to 28%) seasons and least in the winter (4 to 11%). The 2 Texas areas have the highest differences in the fall and winter (2 to 8%) and their lowest differences in the summer (0 to 2%). Between areas, the differences are lowest for the 2 Texas areas (0 to 8%), highest for the Golden Circle areas in the summer and fall (13 to 28%), and highest for Bandelier in the winter and spring (11 to 15%).

The visual ranges for the two alternatives have seasonal and spatial patterns for the eight areas. Except for the winter, the best visibilities are found in the Golden Circle areas (146 to 245 km for SCS and 151 to 298 km for CEC) and the worst are found in the 2 Texas areas (133 to 189 km for SCS and 136 to 228 km for CEC).

Perception of Visibility Effects

Two very important questions with respect to the evaluation of the two scenarios are the questions of visibility impairment and whether or not the CEC alternative would significantly improve visibility over the SCS alternative. With regard to the implementation of the Federal visibility legislation, a critical factor is the definition of visibility impairment. In EPA's visibility rules, visibility impairment is defined as "any humanly perceptible change in visibility (visual range, contrast, coloration) from that which would have existed under natural conditions" and significant impairment is defined as an impairment "which in the judgment of the (EPA) Administrator, interferes with the management, protection, preservation, or enjoyment of the visitors' visual experience of the mandatory Class I area."¹¹ Significant impairment is to be determined on a case-by-case basis. A great deal of uncertainty remains concerning the EPA's visibility regulation with regard to its interpretation in terms of quantitative criteria and implementation.¹¹

The second question concerning significant improvement in regional visibility caused by the CEC alternative over the SCS alternative is addressed in this section. The first question requires data concerning what the visibilities would have been without man-made sources. Visibilities that would have existed under natural conditions are not well characterized. For this reason, this question is not addressed in this section.

The contrast threshold approach discussed under methods, is employed with caution to examine the second question. Upper and lower bounds are set on the percent changes in the visual range that would be perceptible. The lower bound percent change of 5.4% is based on Case B, the observer located outside of the haze, for the probably perceptible criterion and the observer located at the point of maximal impact (see Table IX). The upper-bound percent change of 17.3% is based on Case A, the observer embedded in the haze for the probably perceptible criterion, and for the case of average contrast change (see Table IX). For the lower-bound percent change in visual range, 5-6 out of the 8 areas for each season would show significant improvement in visibility for the CEC alternative over the SCS alternative. For the more stringent upper-bound limit, 4 out of the 8 areas, including Bandelier in the fall, and 3-4 areas located in the Golden Circle region for the summer and fall, would show significant visibility improvement for the CEC alternative over the SCS alternative.

Copper Smelter Contribution to Total Extra Light Extinction

The question concerning the contribution of the 11 southwestern copper smelters to the total extra light extinction, including both the natural and anthropogenic contributions, is addressed in this section. Extra light extinction includes all contributions except light scattering by air molecules called Rayleigh scattering. The percent contribution of the smelters has a wide range (0.1 to 71%) depending on scenario, season, and location. The percent smelter contribution is 2 to 3 times lower for the CEC alternative relative to the SCS alternative, which reflects the 3-times-lower SO_x emissions for the CEC alternative compared with the SCS alternative. This relative difference between scenarios is somewhat lower for the Golden Circle areas. The 2 Texas areas have the lowest smelter contribution (0.5 to 23% for SCS and 0.1 to 8% for CEC); Bandelier has the highest contribution for the winter and spring (25 to 30% for SCS and 9 to 11% for CEC), and the Golden Circle areas have the highest contribution for summer and fall (30 to 71% for SCS and 12 to 44% for CEC). Except for the 2 Texas areas, the highest smelter contribution is in the fall (36 to 71% for SCS and 15 to 44% for CEC) and lowest in the winter (15 to 27% for SCS and 9 to 12% for CEC).

Conclusions

The conclusions for the study as a whole, including the conclusions from the episodic analysis and the statistical analyses of the aerosol and visibility data which are not presented in this paper, are presented in this section. Refer to the final report for the discussion of the complete study. The conclusions are summarized as follows.

- The modeling results show that the CEC alternative would significantly improve visibility in 5-6 out of 8 of the areas studied and would

substantially reduce SO_4 concentrations in all 14 areas.

- For the September 1979 episode, the modeling results indicate that the visibilities in 3 out of 5 areas would improve to better than the average 1979 summer levels if the smelter SO_x emissions were reduced to CEC levels.
- The smelters were found to be a significant contributor (greater than 20% contribution to the total extra light extinction budget which includes all contributions except light-scattering by air molecules called Rayleigh scattering) to visibility reduction in 7 out of 8 of the areas studied.
- The strike period's SO_4 concentrations were found to be substantially reduced from the levels during the non-strike period at almost all of the aerosol monitoring sites studied whereas visibilities were found to have a much less than expected improvement. This contradiction may be caused by uncontrolled factors such as differences between the 2 periods with regard to meteorology and the contributions to visibility reduction from other sources. It is recommended that this apparent contradiction be resolved through a follow-up study that examines in detail the differences in these 2 factors.

Appendix A: Seasonal Regional Transport Model

In this appendix, we describe the methodology for estimating seasonal average particulate sulfate concentrations from sulfur dioxide and primary SO_4 emissions from the smelter sources. The concentrations are estimated for 2° by 2° grid cells that extend vertically to the top of the mixing layer and cover most of the western US (see Figure 3). The smelter emissions were apportioned to the grid array elements according to source location. Seasonal average concentrations were calculated from a two-dimensional eulerian air pollutant transport model.^{12,13}

The model is derived from mass balance equations for primary and secondary pollutants for a system of cells in a two-dimensional array. The secondary pollutant is formed through the chemical conversion of the primary pollutant. The model is analogous to a two-dimensional estuarine water quality model.³² The model accounts for the following atmospheric processes.

- The transformation of the primary to the secondary pollutant.
- The wet and dry deposition of the primary and secondary pollutants.
- The advective transport between cells.
- Vertical mixing up to the top of the mixing layer.

The model is solved for the steady-state case. The following assumptions were made.

- There is no interchange at the top of the mixing layer.
- There is complete mixing within the boundaries of each cell.
- Horizontal dispersion is unimportant relative to advection.

- The transformation and/or removal terms of the mass balance equations are first order in primary and/or secondary pollutant concentrations.
- The wet removal terms of the mass balance equations are first-order in the rate of precipitation.

The input and output variables and the parameters of the model are presented in Table A-I.

Model Equations

The model is derived from the following mass balance equations for the primary and the secondary pollutants. (See Table A-II for definition of symbols.)

Mass Balance Equation for the Primary Pollutant:

$$\frac{dc_{1i}}{dt} V_i = E_{1i} + F_{11i} - F_{10i} - k_{t1} c_{1i} V_i$$

Accumulation	Emissions	Advective Transport In	Advective Transport Out	Transformation
-	$-k_{r1} c_{1i} V_i$	$+ F_{11b1}$	$- F_{10b1}$	
	Removal	Advective Transport In At The Boundary	Advective Transport Out At The Boundary	

(A-1)

Mass Balance Equation for the Secondary Pollutant:

$$\frac{dc_{2i}}{dt} V_i = E_{2i} + F_{21i} - F_{20i} + \delta k_{t1} c_{1i} V_i$$

Accumulation	Emissions	Advective Transport In	Advective Transport Out	Transformation
-	$-k_{r2} c_{2i} V_i$	$+ F_{21b1}$	$- F_{20b1}$	
	Removal	Advective Transport In At The Boundary	Advective Transport Out At The Boundary	

(A-2)

where

$$F_{kIi} = \sum_{j \neq i} c_{kji} U_{ji} \quad (A-3)$$

$$F_{kOi} = \sum_{j \neq i} c_{kij} U_{ij} \quad (A-4)$$

$$F_{kIb_i} = \sum_b c_{kbi} U_{bi} \quad (A-5)$$

$$F_{kOb_i} = \sum_b c_{kib} U_{ib} \quad (A-6)$$

$$c_{kji} = \alpha_{kji} c_{kj} + (1 - \alpha_{kji}) c_{ki} \quad (A-7)$$

$$c_{kij} = \alpha_{kij} c_{ki} + (1 - \alpha_{kij}) c_{kj} \quad (A-8)$$

$$c_{kbi} = \alpha_{kbi} c_{kb_i} + (1 - \alpha_{kbi}) c_{ki} \quad (A-9)$$

$$c_{kib} = \alpha_{kib} c_{ki} + (1 - \alpha_{kib}) c_{kb_i} \quad (A-10)$$

$$U_{ji} = w_{ji} H_{uji} \quad (A-11)$$

$$U_{ij} = w_{ij} H_{uji} \quad (A-12)$$

$$U_{bi} = w_{bi} H_{uji} \quad (A-13)$$

$$U_{ib} = w_{ib} H_{uib} \quad (A-14)$$

$$w_{ji} = w_{ij} \quad (A-15)$$

$$w_{ib} = w_{bi} \quad (A-16)$$

$$V_i = A_i H \quad (A-17)$$

$$k_{rk_i} = (V_{dk_i}/H) + k_{wdk_i} P_i \quad (A-18)$$

$$\delta = M_2/M_1 \quad (A-19)$$

For all cells within the grid array, Eqs. (A-1) and (A-2) under the assumption of steady-state comprise a system of linear equations that can be expressed as the following matrix equations.

$$A_1 C_1 = Q_1 + B_1 \quad (A-20)$$

$$A_2 C_2 = Q_2 + C_1 + B_2 \quad (A-21)$$

where

$$A_k = \begin{bmatrix} a_{k11} & \cdot & \cdot & \cdot & a_{k1n} \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ \cdot & & & & \cdot \\ a_{kn1} & & & & a_{knn} \end{bmatrix} \quad (A-22)$$

$$C_k = \begin{bmatrix} c_{k1} \\ \cdot \\ \cdot \\ \cdot \\ c_{kn} \end{bmatrix} \quad (A-23)$$

$$Q_k = \begin{bmatrix} q_{k1} \\ \cdot \\ \cdot \\ \cdot \\ q_{kn} \end{bmatrix} \quad (A-24)$$

$$B_k = \begin{bmatrix} b_{k1} \\ \cdot \\ \cdot \\ \cdot \\ b_{kn} \end{bmatrix} \quad (A-25)$$

$$a_{11i} = - \sum_{j \neq i} [(1 - \alpha_{1ji})U_{ji} - \alpha_{1ij}U_{ij}] - \sum_b [(1 - \alpha_{1bi})U_{bi} - \alpha_{1ib}U_{ib}] + (k_{ti} + k_{r1i})V_i \quad (A-26)$$

$$a_{1ij} = -\alpha_{1ji}U_{ji} + (1 - \alpha_{1ij})U_{ij} \quad (A-27)$$

$$b_{1i} = \sum_b c_{1bi} [\alpha_{1bi}U_{bi} + (1 - \alpha_{1ib})U_{ib}] \quad (A-28)$$

$$Q_{1i} = E_{1i} \quad (A-29)$$

$$a_{21i} = \{- \sum_{j \neq i} [(1 - \alpha_{2ji})U_{ji} - \alpha_{2ij}U_{ij}] - \sum_b [(1 - \alpha_{2bi})U_{bi} - \alpha_{2ib}U_{ib}] + k_{r2i} V_i\} / (\delta k_{ti} V_i) \quad (A-30)$$

$$a_{2ij} = [-\alpha_{2ji}U_{ji} + (1 - \alpha_{2ij})U_{ij}] / (\delta k_{ti} V_i) \quad (A-31)$$

$$b_{2i} = \{\sum_b c_{2bi} [\alpha_{2bi}U_{bi} + (1 - \alpha_{2ib})U_{ib}]\} / (\delta k_{ti} V_i) \quad (A-32)$$

$$Q_{2i} = E_{2i} / (\delta k_{ti} V_i) \quad (A-33)$$

The elements of the matrix inverse of A_1 represent transfer coefficients between primary emissions, E_{1i} , or boundary elements, b_{1i} , and primary concentrations, c_{1i} . The elements of the matrix inverse of A_2 represent transfer coefficients between primary concentrations, c_{1i} , secondary factorized emissions, Q_{2i} , or factorized boundary elements, b_{2i} , and secondary concentrations, c_{2i} . The transfer coefficients need to be calculated only once for a given time period and set of model parameters and can be used repeatedly for the analysis of alternative policies with different emission source configurations.

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References

1. D. H. Nochumson and M. D. Williams, "Copper Smelters and Atmospheric Visibility in National Parks and Wilderness Areas in the Southwest," prepared by Los Alamos National Laboratory for the US Environmental Protection Agency (March 1983).
2. D. H. Nochumson, "Regional Air Quality in the Four Corners Study Region," Proc. 75th Annual Meeting of the Air Pollution Control Association, New Orleans, Louisiana, June 20-25, 1982 (Accepted for publication in the APCA Journal).
3. D. H. Nochumson, "An Evaluation of Regional Haze Visibility Impacts," The Environmental Professional 4:129 (1982).
4. D. H. Nochumson, "Air Quality in the Four Corners Study Region: Regional Analysis," prepared for the National Commission on Air Quality (NTIS No. PB 81-19862, March 1981).
5. J. Trijonis, "Visibility in the Southwest: An Exploration of the Historical Data Base," Atmospheric Environment 13:833 (June 1979).
6. EPA, "Protecting Visibility, an EPA Report to Congress," EPA-450/5-79-008 (October 1979).
7. E. S. Macias, D. L. Blumenthal, J. A. Anderson, and B. K. Cantrell, "Characterization of Visibility Reducing Aerosols in the Southwestern United States," Interim Report on Project VISTTA, MRI report 78 IR 15-85 (1979).
8. E. S. Macias, J. O. Zwicker, J. R. Ouimette, S. V. Hering, S. K. Friedlander, T. A. Cahill, G. A. Kuhlmeier and L. W. Richards, "Regional Haze Case Studies in the Southwestern US--I. Aerosol Chemical Composition," Atmos. Environ. 15(10/11): 1971-1986 (October/November 1981).
9. C. Mangeng and R. Mead, "Sulfur Dioxide Emissions from Primary Nonferrous Smelters in the Western United States," Los Alamos National Laboratory report LA-8268-MS (August 1980).
10. EPA, "1975 National Emissions Report," EPA-450/2-78-020 (May 1978).
11. Federal Register, Vol. 45, No. 233 (Tuesday, December 2, 1980).
12. D. H. Nochumson, Models for the Long Distance Transport of Atmospheric Sulfur Oxides, Ph.D. dissertation, Harvard University, Cambridge, Massachusetts, January 1978 (Garland Publishing, Inc., New York, 1979).
13. D. H. Nochumson, "Regional Air Quality in the Four Corners Study Region: Modeling Approach," Proc. of the Third Joint Conference on Applications of Air Pollution Meteorology, San Antonio, Texas, January 11-15, 1982.

14. M. Marians and J. Trijonis, "Empirical Studies of the Relationship Between Emissions and visibility in the Southwest," EPA-450/5-79-009 (1979).
15. D. J. Eatough, B. E. Richter, N. L. Eatough, and L. D. Hansen, "Sulfur Chemistry in smelter and Power Plant Plumes in the Western US," Atmos. Environ. 15(10/11): 2241-2254 (October/November 1981).
16. D. J. Eatough, J. J. Christensen, N. L. Eatough, M. W. Hill, T. D. Major, N. F. Mangelson, M. E. Post, J. F. Ryder, L. D. Hansen, R. G. Meisenheimer, and J. W. Fischer, "Sulfur Chemistry in a Copper Smelter Plume," Atmos. Environ. 15(5): 1001-1016 (May 1982).
17. A. Pitchford, M. L. Pitchford, W. C. Malm, R. G. Flocchini, and T. A. Cahill, "Regional Analysis of Factors Affecting Visual Air Quality," Atmos. Environ. 15: 2043-2054 (November 1981).
18. W. C. Malm, E. G. Walther, K. O'Dell, and M. Kleine, "Visibility in the Southwestern United States from Summer 1978 to Spring 1979," Atmos. Environ. 15: 2031-2042 (November 1981).
19. W. E. K. Middleton, Vision Through the Atmosphere (University of Toronto Press, 1952).
20. R. J. Charlson, "Atmospheric Visibility Related to Aerosol Mass Concentration--A Review," Environ. Sci. Tech. 3: 913 (1969).
21. S. K. Friedlander, Smoke, Dust, and Haze (John Wiley and Sons, New York, 1977).
22. W. H. White and P. T. Roberts, "On the Nature and Origin of Visibility Reducing Aerosols in the Los Angeles Air Basin," Atmos. Environ. 11: 803 (1977).
23. D. H. Nochumson, M. Wecksung and F. Gurule, "Potential Future Impacts on Visual Air Quality for Class I Areas," Proc. National Conference on Applied Techniques for Analysis and Management of the Visual Resource, Incline Village, Nevada, April 23-25, 1979.
24. D. A. Latimer, R. W. Bergstrom, S. R. Hayes, M. K. Liu, J. H. Seinfeld, G. F. Whitten, M. A. Wojcik, and M. J. Hillyer, "The Development of Mathematical Models for the Prediction of Atmospheric Visibility Impairment," EPA 450/3-78-110a,b,c (1978).
25. D. H. Nochumson, M. D. Williams, L. Y. Chan, and R. J. Lewis, "User's Manual for the Los Alamos Visibility Model (LAVM)," prepared for US Environmental Protection Agency, Los Alamos National Laboratory report LA-UR-82-1322 (April 1982).

26. J. Trijonis, "Thresholds of Visibility Impairment," prepared by Santa Fe Research for Los Alamos National Laboratory, unpublished data (August 1980).
27. R. W. Mead and G. W. Bonen, "The Non-Ferrous Mining Industry in the American Southwest," prepared for the National Science Foundation by The University of New Mexico, Report No. NE-81(80) WSF-452-1 (July 1980).
28. G. C. Holzworth, "Mixing Heights, Wind Speeds, and Potential for Urban Air Pollution Throughout the Contiguous United States," US Environmental Protection Agency (January 1972).
29. National Weather Service, "Climatological Data, National Summary, Annual 1965-1970," 16-21, No. 13 (1967-71).
30. R. A. Brys and F. K. Hare, World Survey of Climatology, Volume 11, Climates of North America (Elsevier Scientific Publishing Company, New York, 1979).
31. H. L. Crutcher, "Meridional Cross-Sections--Upper Winds over the Northern Hemisphere," US Weather Bureau Technical Paper No. 41 (June 1961).
32. R. V. Thomann, Systems Analysis and Water Quality Management (McGraw-Hill Book Company, 1972).

Figure 1. Location of southwestern copper smelters in study.

Figure 2. Southwestern national parks and wilderness areas in study.

Figure 3. Regional transport modeling boundaries, seasonal model.

Figure 4. Regional transport model sulfate vs historical relationship sulfate, winter 1979.

Figure 5. Pyrometallurgical processing of copper concentrates.

TABLE 1
COPPER SMELTER SULFUR OXIDE EMISSION CONTROL BY STATE, 1960-1979

Year	State	Input Sulfur (kilotons S/yr)	Sulfur Oxide Emissions (kilotons S/yr)	Percent Control
1965	Arizona	839	808	4
	Nevada	49	49	0
	New Mexico	99	99	0
	Utah	238	167	29
	All	1 225	1 123	8
1970	Arizona	1 039	934	8
	Nevada	60	60	0
	New Mexico	87	87	0
	Utah	269	218	19
	All	1 455	1 299	11
1975	Arizona	1 058	664	37
	Nevada	30	30	0
	New Mexico	53	23	60
	Utah	160	77	52
	All	1 306	794	39
1979	Arizona	892	441	51
	Nevada	10	19	0
	New Mexico	319	70	78
	Utah	248	48	80
	All	1 478	578	61

TABLE II
COPPER SMELTER SULFUR OXIDE EMISSIONS BY STATE, 1965-1982
(kilotons SO_x/yr)

Year	State				Totals
	Arizona	Nevada	New Mexico	Utah	
1965	1 615	99	198	334	2 245
1966	1 734	107	228	352	2 421
1967	994	64	135	267	1 460
1968	1 108	81	206	344	1 739
1969	1 700	118	208	437	2 463
1970	1 869	121	174	436	2 600
1971	1 745	116	154	378	2 393
1972	2 034	113	159	336	2 642
1973	2 110	144	148	327	2 729
1974	1 741	110	117	273	2 241
1975	1 327	61	46	154	1 588
1976	1 009	---	---	---	---
1977	736	---	---	---	---
1978	774	115	---	---	---
1979	882	38	140	97	1 157
1980	638	87	---	---	---
1981	874	---	---	---	---
1982	411	---	---	---	---

TABLE III
COPPER SMELTERS IN STUDY

Name	Location
ASARCO	Hayden, AZ
Inspiration	Miami, AZ
Kennecott	Hayden, AZ
	McGill, NV
	Hurley, NM
	Garfield, UT
Magma	San Manuel, AZ
Phelps Dodge	Ajo, AZ
	Douglas, AZ
	Morenci, AZ
	Hidalgo, NM

TABLE IV
PROPOSED MULTIPOINT ROLLBACK EMISSION LIMITS
FOR SULFUR DIOXIDE--ANNUAL AVERAGES

Smelter	Location	Emission Limit (lb/hr)
ASARCO	Hayden, Arizona	9,521
Inspiration	Miami, Arizona	3,163
Kennecott	Hayden, Arizona	7,790
	McGill, Nevada	21,800
	Hurley, New Mexico	7,000
	Garfield, Utah	18,200
Magma	San Manuel, Arizona	18,275
Phelps Dodge	Ajo, Arizona	8,900
	Douglas, Arizona	15,675
	Morenci, Arizona	10,505

TABLE V
NUMBER OF EXCEEDANCES OF THE
NATIONAL AMBIENT AIR QUALITY STANDARD FOR SULFUR DIOXIDE, ARIZONA SMELTERS

Smelter	Location	Year	Number of Exceedances	
			3-hour Limit	24-hour Limit
Phelps Dodge	Ajo, Arizona	1977	2	1
		1978	5	2
		1979	0	2
		1980	8	2
		1981	5	1
	Douglas, Arizona	1977	14	1
		1978	7	0
		1979	12	6
		1980	8	0
		1981	20	1
	Morenci, Arizona	1977	61	17
		1978	44	11
		1979	27	5
		1980	73	28
		1981	89	42
ASARCO/Kennecott	Hayden Arizona	1977	102	84
		1978	13	9
		1979	40	21
		1980	13	6
		1981	17	12
Inspiration	Miami, Arizona	1977	50	22
		1978	34	14
		1979	56	21
		1980	13	5
		1981	31	10
Magma	San Manuel, Arizona	1977	22	2
		1978	24	3
		1979	18	6
		1980	7	0
		1981	10	1

*Both smelters are located in the same town. The number of exceedances are reported jointly for the two smelters.

TABLE VI
DEPOSITION PARAMETERS, SEASONAL MODEL

Parameter	Units	Species	
		SO ₂	SO ₄
Dry deposition velocity	ms ⁻¹	0.01	0.002
Wet deposition rate parameter	s ⁻¹ /(in/yr)	1.4 x 10 ⁻⁷	1.4 x 10 ⁻⁷

TABLE VII
CHEMICAL CONVERSION RATES OF SULFUR DIOXIDE
TO SULFATES, SEASONAL MODEL (10^{-6} s^{-1})

Season	Calibrated	Based on Plume Measurements
Winter	1.3	0.808
Spring	2.7	2.67
Summer	2.0	4.88
Fall	1.4	1.07

TABLE VIII
SEASONAL REGIONAL TRANSPORT MODEL VERSUS THE HISTORICAL RELATIONSHIP,
MEASURES OF PERFORMANCE

Season	Means ($\mu\text{g}/\text{m}^3$)		Standard Devia- tion ($\mu\text{g}/\text{m}^3$)		Mean Squared Difference ($\mu\text{g}/\text{m}^3$) ²	Correlation Coefficient
	RTM ^a	HR ^b	RTM ^a	HR ^b		
Winter	0.540	0.548	0.387	0.348	0.0233	0.910
Spring	0.799	0.776	0.489	0.492	0.0965	0.781
Summer	1.05	1.04	0.698	0.646	0.182	0.781
Fall	1.08	1.03	0.692	0.633	0.0518	0.942

RTM = regional transport model.

HR = historical relationship.

MSD = $(1/N) \sum [(SO_4)_{HR} - (SO_4)_{RTM}]^2$
MSD = mean squared difference
N = 11.

TABLE IX
THRESHOLDS OF PERCEPTION

	Case A--Observer Embedded in Plume or Haze			Case B--Observer Outside Plume or Haze		
	Percent Change in Visual Range			Percent Change in Visual Range		
	ΔC	Point of Maximal Impact	Case of Average Contrast Change	ΔC	Point of Maximal Impact	Case of Average Contrast Change
Possibly Perceptible	0.02	5.4	8.7	0.01	2.7	4.3
Probably Perceptible	0.04	10.9	17.3	0.02	5.4	8.7
Definitely Perceptible	0.06	16.3	26.0	0.04	10.9	17.3

TABLE 1
COPPER SMELTERS UNIT PROCESSES

Smelter	Location	1979					Expected Future Configuration				
		Roasters	Furnaces	Con- verters	SO _x Control		Roasters	Furnaces	Con- verters	SO _x Control	
					Acid Plants	Addi- tional				Acid Plants	Addi- tional
ASARCO	Hayden, AZ	12 MH	2 R	5 PS	1 SC	---	---	FL	OE ^a	1 SC, 1 DC	---
Inspiration	Miami, AZ	---	1 E	5 H	1 DC	---	b	C	d	c	---
Kennecott	Hayden, AZ	1 EG	1 R	3 PS	1 DC	---	e	e	e	e	---
	McGill, NV	---	2 R	4 PS ^g	---	---	---	c	f	1 SC ^h	---
Magma Phelps Dodge	Marley, NM	---	1 R	4 PS	1 DC	---	---	F	i	j	1 LP
	Garfield, UT	---	3 R	4 F	4 SC	---	---	c, k	c, k	c, k	---
	San Manuel, AZ	---	3 R	6 PS	2 SC	---	---	c	c	c	---
	Ajo, AZ	---	1 R	3 PS	1 SC	---	---	OS or FL	OE ^a	1 SC ^l	CGCS
	Douglas, AZ	24 MH	3 R	5 PS	---	---	c	c	c	c	---
	Morenci, AZ	---	5 R ^m	9 PS	2 SC	---	---	OS or FL	OE ^a	---	---
	Hidalgo, NM	---	1 FL	5 PS	1 DC	---	---	c, k	c, k	c, k	---

MH = multiple hearth
E = electric
OS = oxygen sprinkle
F = finishing
DC = double contact

FS = fluo-solids
FL = flash
H = hoboken
OE = oxygen enrichment
LP = SO₂ liquefaction plant

R = reverberatory
R = Moranda
PS = Pierce Smith
SC = single contact
CGCS = coal gas cleaning system

^aBeing considered.

^bThe adding of a roaster is being considered.

^cThe modification of the existing converters to their own design is being considered.

^dModifications or replacement of the current unit process is under study.

^eSc modifications or replacement to the current unit process has been proposed.

^fThe addition of hooding is being considered.

^gTwo of the converters are currently being operated.

^hThe White Pine Power Project (WPPP) has proposed to locate a coal-fired power plant in the same general area as the McGill smelter. McGill and WPPP have been negotiating with EPA for an emission tradeoff where the power plant would be allowed a lower SO_x control level and in turn would pay for a single-contact acid plant to be installed at McGill.

ⁱThe installation of secondary hoods on the converters is planned.

^jA larger fan is expected to replace the existing fan and the tail gas is expected to be rerouted to the main stack.

^kThis is a relatively new smelter. The new smelter at Hidalgo began operation in 1976 and the one at Garfield began operation in 1978.

^lThere are plans to upgrade the acid plant.

^mThree of the green feed reverberatory furnaces are currently in operation.

TABLE XI
SULFUR DIOXIDE EMISSIONS, SEASONAL/ANNUAL
(tons sulfur/day)

Smelter	Location	1979					Constant Emission Control Scenario				
		Winter	Spring	Summer	Fall	Annual	Winter	Spring	Summer	Fall	Annual
ASARCO	Hayden, AZ	197.4	170.5	159.2	151.6	169.2	29.3	30.1	29.3	27.1	28.9
Inspiration	Miami, AZ	61.1	57.6	85.7	54.0	64.6	25.3	25.8	19.5	24.6	23.8
Kennecott	Hayden, AZ	23.4	9.0	18.2	71.4	30.6	30.4	21.0	26.2	34.4	28.0
	McGill, NV	63.0	---	32.4	114.3	52.5	30.7	---	15.4	52.4	24.6
	Hurley, NM	111.0	113.8	106.4	101.8	108.2	29.3	30.1	28.1	26.9	28.6
	Garfield, UT	90.0	127.1	158.5	154.2	132.7	90.0 ^a	127.1 ^a	158.1 ^a	154.2 ^a	132.7 ^a
Magma	San Manuel, AZ	267.4	293.3	357.7	324.5	311.1	71.8	70.8	76.9	77.8	74.6
Phelps Dodge	Ajo, AZ	59.7	74.2	81.5	61.9	69.3	40.1	43.5	32.2	40.9	39.2
	Douglas, AZ	244.5	356.3	387.7	452.8	361.0	34.1	49.7	53.8	62.8	50.2
	Morenci, AZ	218.7	238.6	190.7	164.1	202.8	46.6	49.7	39.8	37.4	43.4
	Hidalgo, NM	86.4	66.6	65.6	115.2	83.8	86.4 ^a	66.6 ^a	65.6 ^a	115.2 ^a	83.8 ^a
TOTALS		1 422.6	1 507.0	1 643.6	1 765.8	1 585.8	514.0	514.4	545.3	653.7	557.6

^aThe 1979 emissions meet the constant emission control limits.

TABLE XII
1979 SMELTER OPERATING RATES
SEASONAL/ANNUAL
(tons input sulfur/day)

Smelter	Location	Winter	Spring	Summer	Fall	Annual
ASARCO	Hayden, AZ	268	274	268	248	264
Inspiration	Miami, AZ	374	331	250	316	305
Kennecott	Hayden, AZ	281	194	242	318	259
	McGill, NV	64	---	33	116	54
	Hurley, NM	285	296	277	265	282
	Garfield, UT	639	772	650	662	681
Magma	San Manuel, AZ	542	534	580	588	563
Phelps Dodge	Ajo, AZ	60	74	82	62	69
	Douglas, AZ	250	364	395	460	368
	Morenci, AZ	579	618	495	465	539
	Hidalgo, NM	708	537	566	553	590
TOTALS		4 000	3 954	3 838	4 053	3 974

^aThe smelter was not operating during this season.

TABLE XIII

RELATIVE HUMIDITIES, SEASONAL

<u>Location</u>	<u>Winter</u>	<u>Spring</u>	<u>Summer</u>	<u>Fall</u>
Grand Canyon	40	25	35	35
Bryce Canyon	45	30	30	35
Canyonlands	45	30	35	35
Arches	50	30	30	35
Mesa Verde	50	30	40	40
Chiricahua	30	25	30	30
Galluro	30	25	30	30
Mazatzal	35	25	35	30
Saguara	30	25	30	30
Bandelier	50	30	40	55
Gila	30	25	30	35
Wheeler	55	35	45	60
Big Bend	55	45	45	55
Guadalupe	45	35	40	45

TABLE XIV

MEDIAN VISUAL RANGE BY 1979 SEASON (km)

<u>Location</u>	<u>Winter</u>	<u>Spring</u>	<u>Summer</u>	<u>Fall</u>
Grand Canyon	245	169	181	253
Bryce Canyon	205	162	182	241
Canyonlands	186	189	189	206
Mesa Verde	169	164	174	194
Bandelier	177	165	140	176
Big Bend	203	143	140	146
Carlsbad	210*	144	133	152

*An average of the 1979 and 1980 winter medians were used because the sample size was small for the winter of 1979.

TABLE XV
SEASONAL SMELTER SULFATE CONCENTRATION ESTIMATES ($\mu\text{g}/\text{m}^3$)

Location	Winter		Spring		Summer		Fall	
	SCS	CEC	SCS	CEC	SCS	CEC	SCS	CEC
<u>Golden Circle</u>								
Grand Canyon	0.34	0.13	0.47	0.17	1.03	0.28	1.11	0.35
Bryce Canyon	0.27	0.14	0.34	0.15	0.33	0.27	0.82	0.30
Canyonlands	0.34	0.16	0.56	0.22	1.05	0.31	0.84	0.30
Arches	0.34	0.16	0.56	0.22	1.05	0.31	0.83	0.30
Mesa Verde	0.39	0.15	0.74	0.24	1.14	0.30	0.82	0.26
	0.34 $\pm$ 0.043 ^a	0.15 $\pm$ 0.013 ^a	0.53 $\pm$ 0.15 ^a	0.20 $\pm$ 0.038 ^a	1.02 $\pm$ 0.11 ^a	0.29 $\pm$ 0.019 ^a	0.88 $\pm$ 0.13 ^a	0.30 $\pm$ 0.032 ^a
<u>Arizona</u>								
Chiricahua	0.87	0.26	1.15	0.33	1.47	0.37	1.80	0.53
Gilguro	0.94	0.28	1.19	0.35	1.66	0.42	1.93	0.56
Mazatzal	0.61	0.20	0.79	0.25	1.45	0.38	1.61	0.49
Saguara	0.63	0.20	0.77	0.24	1.27	0.33	1.66	0.50
	0.76 $\pm$ 0.17 ^a	0.24 $\pm$ 0.041 ^a	0.98 $\pm$ 0.22 ^a	0.29 $\pm$ 0.056 ^a	1.46 $\pm$ 0.16 ^a	0.38 $\pm$ 0.037 ^a	1.75 $\pm$ 0.14 ^a	0.52 $\pm$ 0.032 ^a
<u>New Mexico</u>								
Bandelier	0.52	0.16	0.97	0.28	0.92	0.23	0.68	0.20
Gila	1.02	0.29	1.47	0.41	1.58	0.40	1.48	0.43
Wheeler Peak	0.43	0.13	0.86	0.25	0.82	0.21	0.59	0.18
	0.66 $\pm$ 0.32 ^a	0.19 $\pm$ 0.085 ^a	1.10 $\pm$ 0.32 ^a	0.31 $\pm$ 0.085 ^a	1.11 $\pm$ 0.41 ^a	0.28 $\pm$ 0.10 ^a	0.92 $\pm$ 0.49 ^a	0.27 $\pm$ 0.14 ^a
<u>Texas</u>								
Big Bend	0.082	0.026	0.13	0.036	0.014	0.0038	0.18	0.052
Guadalupe Mts.	0.36	0.11	0.57	0.16	0.14	0.044	0.43	0.13
	0.22 $\pm$ 0.20 ^a	0.068 $\pm$ 0.059 ^a	0.35 $\pm$ 0.31 ^a	0.098 $\pm$ 0.088 ^a	0.077 $\pm$ 0.089 ^a	0.024 $\pm$ 0.028 ^a	0.30 $\pm$ 0.18 ^a	0.091 $\pm$ 0.055 ^a
<u>All Sites</u>	0.51 $\pm$ 0.27 ^a	0.17 $\pm$ 0.071 ^a	0.76 $\pm$ 0.36 ^a	0.24 $\pm$ 0.093 ^a	1.03 $\pm$ 0.48 ^a	0.28 $\pm$ 0.12 ^a	1.06 $\pm$ 0.55 ^a	0.33 $\pm$ 0.16 ^a

^amean $\pm$ standard deviation.

TABLE XVI
VISUAL RANGE BY SEASON (km)

Location	Winter			Spring			Summer			Fall		
	SCS	CEC	% Dif- ference	SCS	CEC	% Dif- ference	SCS	CEC	% Dif- ference	SCS	CEC	% Dif- ference
<u>Golden Circle</u>												
Grand Canyon	245	263	7.3	169	179	5.9	161	217	19.9	233	298	27.9
Bryce Canyon	205	213	3.9	162	168	3.7	182	206	13.2	241	285	18.2
Canyonlands	186	195	4.8	189	204	7.9	189	228	20.6	206	239	16.0
Arches	186	196	5.4	189	204	7.9	189	225	19.0	206	238	15.5
Mesa Verde	169	181	7.1	164	181	10.4	174	216	24.1	194	226	16.5
	198±29 ^a	210±32 ^a	5.7±1.5 ^a	175±13 ^a	187±16 ^a	7.2±2.5 ^a	183±6 ^a	218±9 ^a	19.4±3.9 ^a	216±20 ^a	257±32 ^a	18.8±5.2 ^a
<u>New Mexico</u>												
Bandelier	177	197	11.3	165	190	15.2	140	160	14.3	176	207	17.6
<u>Texas</u>												
Big Bend	203	207	2.0	142	146	2.1	140	140	0.0	146	151	3.4
Guadalupe Mts.	210	227	8.1	144	155	7.6	133	136	2.2	152	163	7.2
	206±5 ^a	217±14 ^a	5.0±4.3 ^a	144±7 ^a	150±6 ^a	4.8±3.9 ^a	136±5 ^a	138±3 ^a	1.1±1.6 ^a	149±4 ^a	157±8 ^a	5.3±2.7 ^a
<u>All Sites</u>	198±24 ^a	210±25 ^a	6.2±2.8 ^a	166±17 ^a	178±21 ^a	7.6±4.0 ^a	166±24 ^a	191±39 ^a	14.2±8.8 ^a	194±35 ^a	226±52 ^a	15.2±7.4 ^a

^amean ± standard deviation.

TABLE XVII

PERCENT EXTRA EXTINCTION DUE TO THE COPPER SMELTERS

Location	Winter		Spring		Summer		Fall	
	SCS	CEC	SCS	CEC	SCS	CEC	SCS	CEC
<u>Golden Circle</u>								
Grand Canyon	26.6	12.2	14.2	5.5	40.1	15.7	71.1	44.0
Bryce Canyon	15.4	8.8	10.1	4.8	29.6	11.9	54.4	30.1
Canyonlands	16.3	8.6	21.5	9.7	43.9	18.7	41.0	19.8
Arches	17.8	9.4	21.6	9.7	40.5	16.7	40.6	19.6
Mesa Verde	17.7	7.5	22.5	8.6	44.0	17.4	38.4	16.7
	18.8 $\pm$ 4.5 ^a	9.3 $\pm$ 1.8 ^a	18.9 $\pm$ 5.5 ^a	7.7 $\pm$ 2.3 ^a	39.6 $\pm$ 5.9 ^a	16.1 $\pm$ 2.6 ^a	49.1 $\pm$ 13.8 ^a	26.0 $\pm$ 11.2 ^a
<u>New Mexico</u>								
Bandelier	25.2	9.3	29.9	10.9	25.7	8.1	36.7	14.7
<u>Texas</u>								
Big Bend	6.2	2.1	4.3	1.2	0.46	0.12	7.3	2.3
Guadalupe Mts.	22.6	8.1	15.6	4.8	4.6	1.2	15.1	5.0
	14.4 $\pm$ 1.6 ^a	5.1 $\pm$ 4.2 ^a	10.0 $\pm$ 8.0 ^a	3.0 $\pm$ 2.5 ^a	2.5 $\pm$ 2.9 ^a	0.7 $\pm$ 0.8 ^a	11.2 $\pm$ 5.5 ^a	3.6 $\pm$ 1.9 ^a
<u>All Sites</u>	18.5 $\pm$ 6.5 ^a	8.2 $\pm$ 2.8 ^a	17.4 $\pm$ 8.1 ^a	6.9 $\pm$ 3.3 ^a	28.6 $\pm$ 17.4 ^a	11.2 $\pm$ 7.3 ^a	38.1 $\pm$ 20.2 ^a	19.0 $\pm$ 13.4 ^a

^amean $\pm$ standard deviation.

TABLE A-1
INPUT-OUTPUT VARIABLES AND MODEL PARAMETERS

Input Variables^a

- o Primary and secondary pollutant emission rates
- o Mixing layer height
- o Two-dimensional air flow within the mixing layer (frequency of direction and speed normal to the grid cell faces)
- o Precipitation
- o Cell dimensions

Output Variables^{a,c}

- o Concentration
- o Deposition

Parameters^{a,b}

- o Conversion rate for the primary pollutant
- o Dry deposition velocities^c
- o Wet deposition rate constants^c

^aBy grid cell and averaging period.

^bThey are lumped parameters representing averaged values over space (grid cell) and time (averaging time).

^cFor primary and secondary pollutants.

TABLE A-11

SYMBOLS

- E_{ki} = the emission rate for species k in cell i .
- c_{ki} = the concentration of species k in cell i .
- c_{kij} = the concentration of species k at the interface between cells i and j .
- c_{kbi} = the concentration of species k at the boundary of cell i . It is zero for interior cells.
- a_{kij} = a weighting factor that relates the concentrations in two adjacent cells to the concentrations at the cell face when advective flow is from cell i to cell j .
- a_{kbi} = analogous to a_{kij} but it applies when a cell is at the boundary of the system of grid cells.
- U_{ij} = the volumetric air flow rate from cell i to cell j .
- U_{bi} = the volumetric air flow rate across the boundary of cell i . It is zero for interior cells.
- w_{ij} = the length of the cell face between cells i and j .
- H = the depth of the mixing layer.
- w_{bi} = the length of the cell face between the boundary and cell i .
- u_{ij} = the average wind speed through the mixing depth when the direction of the wind component perpendicular to the cell face is from cell i to cell j .
- u_{bi} = the average wind speed through the mixing depth when the direction of the component perpendicular to the cell face is from the boundary to cell i . It is zero for interior cells.
- A_i = the ground area of cell i .
- V_i = the volume of cell i .
- k_{ti} = the first order transformation rate parameter for cell i .
- k_{rki} = the first order removal rate parameter for species k in cell i .
- $V_{dk i}$ = the dry deposition velocity for species k in cell i .
- $k_{wdk i}$ = the first order wet deposition rate parameter of species k in cell i .
- P_i = the precipitation rate in cell i .
- δ = the ratio of the molecular weight of the secondary pollutant, M_2 , to the molecular weight of the primary pollutant, M_1 .