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The Implications of a Stochastic Approach to Air-Quality Regulations

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THE IMPLICATIONS OF A STOCHASTIC APPROACH
TO AIR-QUALITY REGULATIONS

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EXECUTIVE SUMMARY

Introduction

This study explores the viability of a stochastic approach to air quality regulations. The stochastic approach considered here is one which incorporates the variability which exists in sulfur dioxide (SO_2) emissions from coal-fired power plants. Emission variability arises from a combination of many factors including variability in the composition of as-received coal such as sulfur content, moisture content, ash content, and heating value, as well as variability which is introduced in power plant operations. The stochastic approach as conceived in this study addresses variability by taking the SO_2 emission rate to be a random variable with specified statistics. Given the statistical description of the emission rate and known meteorological conditions, it is possible to predict the probability of a facility exceeding a specified emission limit or violating an established air quality standard.

This study also investigates the implications of accounting for emissions variability by allowing compliance to be interpreted as an allowable probability of occurrence of given events. For example, compliance with an emission limit could be defined as the probability of exceeding a specified emission value, such as 1.2 lbs SO_2 /MMBtu, being less than 1%. In contrast, compliance is currently taken to mean that this limit shall never be exceeded, i.e., no exceedance probability is allowed.

The focus of this study is on the economic benefits offered to facilities through the greater flexibility of the stochastic approach as compared with possible changes in air quality and health effects which could result. The range of plant designs considered is by no means exhaustive but is, for the most part, limited to the concept of emission banking. The motivation for this banking concept is the reduction in power plant capital and operating costs through the elimination of redundancy in the flue gas desulfurization (FGD) system. By utilizing an FGD system with a greater design removal efficiency than currently required, less SO_2 is emitted during periods when the FGD system is fully operational. The difference between actual emissions and allowable emissions

are considered as banked emissions. During FGD system upset situations, emissions would be greater than the currently allowable limit since no reserve FGD capacity is available. Under upset conditions, some banked emissions are withdrawn. This mode of operations is not allowed by existing regulations but is feasible with the stochastic approach.

FGD Systems Cost

Plant capital and operating costs are developed for two different scenarios. A plant designed to be in compliance with existing air quality regulations (base case) is developed for both a plant sited in the eastern United States burning a high-sulfur eastern coal and a plant sited in the western United States burning a low-sulfur western coal. Alternative plant scenarios are developed for both the eastern and western plants which take advantage of the banking concept allowed in the stochastic approach. In this study all power plants are assumed to have a gross rating of 500 MWe and utilize a typical pulverized coal combustor. The eastern plant scenarios are assumed to use a southeastern Ohio Pittsburgh seam bituminous coal having a mean heating value of 11,500 Btu/lb and a mean sulfur content of 3.35% by weight before beneficiation. The western plant scenarios are assumed to use a Wyoming subbituminous coal having a mean heating value of 9000 Btu/lb and mean sulfur content of 0.5% by weight. The sulfur removal strategy for the eastern base case is to remove 14% of the coal sulfur by beneficiation followed by an additional 87% removal through scrubbing providing a total sulfur removal capability of 89%. The FGD system for this plant consists of 5-125 MW capacity (4 operating + 1 spare, 25% sparing), wet-lime scrubber modules. The eastern coal alternative plant design also utilizes cleaned coal. However, the design FGD removal efficiency is increased to 93% while no sparing is provided (4-125 MW scrubber modules). The greater removal efficiency is required, in part, to offset greater emissions which could occur during upsets since no backup scrubber modules are available. When all four modules are fully operative an overall sulfur removal (including beneficiation) of 94% will be realized. The sulfur removal strategy for the western base case assumes a continuous FGD removal efficiency of 70%

utilizing 5-125 MW capacity dry scrubber modules (4 operating + 1 spare). Beneficiation is not considered for the western coal scenarios since it is typically not effective on subbituminous coals. The western coal alternative scenario involves no sparing and utilizes 4-125 MW capacity dry scrubber modules having design removal efficiencies of 80%.

Using SO₂ emission variability derived from time-series analysis of power plant data and typical "down time" for FGD systems, emission rate probability distributions are constructed for the scenarios considered. For the eastern coal scenario the alternative plant design has a mean emission rate 10% less than the base case due to the greater FGD design removal efficiency; however, the emission rate standard deviation for the alternative design is about 2.5 times greater than the base case standard deviation. This is due to the increased emissions which occur in the alternative design during upset conditions as a result of the lack of sparing in the FGD system. For the western scenario, the mean emission rate for the alternative plant design is 20% less than that for the base case, while the alternative plant design emission rate standard deviation is 20% greater than that for the base case.

The banking concept for dealing with FGD upset conditions becomes apparent by analyzing the emission rate probability distribution. The eastern alternative produces greater (withdrawn) emissions than the eastern base case 7% of the time which is offset by lower (banked) emissions 39% of the time. The western alternative shows higher (withdrawn) emissions 2% of the time in contrast to lower (banked) emissions 51% of the time.

Plant capital, operating, and maintenance costs are calculated using relative costs given in the literature and using a coal-fired power plant economic performance model developed for the Department of Energy. All costs were adjusted to 1981 dollars using appropriate escalation factors. For the eastern coal scenario, the total alternative plant design FGD system cost is about 2% less than the total FGD system cost for the base case design. This cost difference is a result of about a 1% capital cost saving since no redundancy is purchased and about a 2% saving in O and M costs due to reduced maintenance costs and lower FGD system power

requirements. For the western coal scenario, total FGD systems cost differences between the base case and alternative plant designs are negligible. While the alternative plant design has a slightly lower capital cost than the base case, the O and M costs are greater due to increased sorbent requirements and a greater volume of solid waste requiring disposal.

Air Quality

Short-term air quality impacts are defined in terms of the probability of violating (two or more exceedances in one year) a 24-hr standard for SO₂. The standard used here is 30 µg/m³. This value can be interpreted as the portion of the full Prevention of Significant Deterioration (PSD) increment (91 µg/m³) which is available as a result of either a specific State Implementation Plan (SIP) requirement or the background air quality. Base case and alternative plant design air quality impacts are assessed for a single isolated facility (single-source analysis) and for multiple facilities (multi-source analysis) sited in the study region.

In the single source analysis for the eastern coal scenario, the maximum violation probability, under typical meteorological conditions, is 0.15% for the base case and 4.15% for the alternative plant design. While the relative difference in violation probabilities is significant, violation probabilities for both cases are acceptably low. The greater violation probability exhibited by the alternative plant design is a result of the relatively higher emissions which occur during FGD system upset conditions. This situation can be mitigated, in part, by including a taller stack in the alternative plant design. This reduces the alternative design maximum violation probability by about one-half. The use of tall stacks is forbidden under present regulations. This exclusion is designed to reduce long-range transport of SO₂ downwind of a facility and to reduce near-source ground-level concentrations by an overall reduction of SO₂ emitted. Since the alternative plant design results in total emissions which are approximately 10% less than those allowed under existing

regulations and since the tall stack is used in this analysis for the purpose of mitigating episodes, it appears that the use of a tall stack in this situation does not strongly contradict the intent of the tall stack prohibition. Violation probabilities in the western coal scenario are negligible for both the base case and alternative plant design.

Incremental ground-level annual-average SO_2 concentrations are predicted to be uniformly lower for the alternative plant designs. For the eastern coal scenario, the alternative plant design produces annual-average concentrations 10% lower than the base case and for the western coal scenario, the alternative plant design produces annual-average concentrations 20% lower than the base case.

For both eastern and western coal scenarios, the alternative plant design produces excursions in short-term air quality above that predicted to be produced by a plant designed in compliance with current regulations; however, the alternative plant design offers overall reductions in SO_2 emissions and improvements in long-term air quality.

Air quality impacts resulting from the operations of five facilities located in the study region are assessed. Violation probabilities resulting from the operation of five distributed facilities having the eastern coal alternative plant design are predicted and compared with predicted violation probabilities for five facilities operating with the base case plant design. As expected, the emissions from the additional sources have caused violation probabilities to increase with respect to the single source results; however, violation probabilities for the base case increase more than those for the alternative plant design. In contrast to the single source results, multi-source base case and alternative plant design violation probabilities are comparable and remain relatively low, on the order of 10%.

The operation of multiple facilities having the alternative plant design will not produce significantly increased excursion in short-term air quality when compared with the operation of multiple facilities designed in compliance with current regulations. The alternative plant design will produce significantly reduced total SO_2 emissions and lesser long term air quality impacts.

With the addition of more facilities, predicted violation probabilities for the alternative plant design become less than the violation probabilities predicted for comparably sited facilities with the base case design. This suggests that as the number of facilities sited within a given region increases and as the available air quality increment decreases, stochastic air quality regulations could provide facility operators sufficient flexibility to site a greater number of facilities in the region before the full PSD increment is consumed.

Health Effects

Differences in acute health effects which may occur as a result of the operation of a facility utilizing the eastern coal alternative plant design are addressed. The analysis is based on the probability of 24 hr-averaged ground-level SO_2 concentrations exceeding threshold values established for morbidity and mortality. The threshold value used in assessing changes in morbidity is the National Primary Standard of $365 \mu\text{g}/\text{m}^3$ and the threshold value used for assessing changes in mortality is $500 \mu\text{g}/\text{m}^3$ as suggested by the World Health Organization. Worst case assumptions are made concerning the nature of air quality effects on morbidity and mortality. Using population distributions for a typical urban/rural area taken from 1970 census data, exposure probabilities are derived as a function of the population exposed.

Using conservative assumptions regarding the health risk of exposure to levels of SO_2 above the threshold values on the sensitive fraction of the population, changes in health risk which could occur within the study region are estimated. Predicted probabilities of exceeding threshold values are larger for the alternative plant design than for the base case resulting in a relative increase in expected health effects. Exceedance probabilities with respect to the morbidity threshold are low, less than 7.5% for base case and less than 15% for the alternative plant design. Exceedance probabilities with respect to the mortality threshold are negligible, less than $10^{-4}\%$ for the base case and less than $10^{-3}\%$ for the alternative plant design. The operation of a single facility with the alternative plant design would result in a total increase in risk of

mortality for an individual in the affected population of less than 10^{-7} . Similarly, the increase in risk of morbidity is less than 10^{-3} . These increases in health risks, although small, are significantly reduced by including a taller stack in the alternative plant design.

Changes in synergistic acute health effects as a result of changes in short-term air quality resulting from the operation of multiple facilities utilizing the alternative plant design are insignificant. This is due to the fact that multi-source exceedance probabilities for the alternative plant design are comparable to exceedance probabilities predicted for multiple facilities utilizing the base case design.

Emission Limits

Emissions from power plants are limited through restrictions imposed by State Implementation Plans (SIPs). Emission limits vary from state to state as well as varying within a given state or a given Air Quality Control Region (AQCR). Not only do emission limits vary, but techniques to establish compliance with these limits vary among states. Recently, Indiana proposed to use 30 day rolling average emissions as a basis for establishing SIP emission limit enforcement priorities. Emission limit compliance based on a 30 day rolling average has generated considerable interest recently and has been suggested as a possible regulatory change on a national basis. This extended averaging procedure is attractive to power plant operators since it offers them greater operating flexibility in meeting emission limits.

In light of the attention given the 30 day rolling average, this study addresses the effects of the procedure on air quality. By comparing the statistics of daily-averaged emission data to the statistics of the same emission data after a 30 day rolling average, changes in the probability of exceeding a given emission limit is determined. By assuming a level of risk of exceeding the emission limit that a facility operator is willing to accept, limits of increased operating flexibility resulting from the 30 day averaging are defined in terms of this acceptable level of risk.

Using the statistical analysis of power plant emission data and an emission limit of 1.2 lbs SO₂/MMBtu, it is determined that the 30-day rolling average procedure offers facility operators significantly improved flexibility in complying with emission limits. However, this procedure would allow an overall increase in SO₂ emissions which could exceed 20%. This would measurably decrease long- and short-term air quality. Furthermore, it is found that defining an emission limit of 1.2 lbs SO₂/MMBtu based on 30 day-averaged emissions data is equivalent to increasing an emission limit based on 24 hr-averaged data to as much as 3.5 lbs SO₂/MMBtu.

As an alternative method for providing plant operators with greater flexibility in complying with emission limits, compliance could be based on an allowable probability of exceeding the given limit. While this technique would not likely offer as much flexibility as the 30 day rolling average, an allowable exceedance probability could be established so as to significantly increase operational flexibility but without reducing air quality.

Conclusions and Recommendations

While the differences in cost between alternative and base case plant designs are small, these relative costs do suggest that the stochastic approach offers power plant operators greater flexibility without any additional expense and without degrading air quality or affecting public health. Furthermore, conservative assumptions are used in developing relative costs, and site and utility-grid specific factors have not been considered in this study. The consideration of these factors would likely demonstrate additional benefits of the stochastic approach. For example, by allowing additional operating hours during upset conditions, plant shutdowns may be postponed for some hours, resulting in longer and potentially less damaging plant shutdown cycles. These longer shutdown cycles may also allow the grid manager to keep a facility generating for an additional few hours, stabilizing the entire grid, and reducing the demand placed on expensive replacement power. The flexibility of the stochastic approach could, in some instances, make the use of a local coal a more

viable option. A savings of \$1.00 per ton in coal transportation costs would result in a saving of approximately \$50,000,000 over the life of a 500 MWe facility.

Although the analysis presented here is not exhaustive, the results indicate that a stochastic approach to air quality regulations has merit and is worthy of further study. Such studies should be narrower than this study and focus more on site specific factors.

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ABSTRACT

A study is performed to compare the flue gas desulfurization capital, operating, and maintenance costs, air quality impacts, and health effects between coal-fired power plants designed to be in compliance with current air quality regulations and emission limits (base cases) and coal-fired power plants that might be designed under more flexible stochastic regulations (alternatives). The alternative plant designs, for the most part, deal with the elimination of reserve flue gas desulfurization system capacity. The use of spare scrubbers is common practice among utilities. The elimination of this sparing offers lower plant capital costs but leads to greater sulfur dioxide emissions during upset situations. The alternative plant designs are selected to minimize these higher emission rates and the analysis performed indicates that changes in air quality and health effects are negligible. It is also determined that the use of a taller stack is an effective method to further reduce impacts of upset conditions. The alternative plant designs considered here are found to emit less sulfur dioxide in the long term. Plant flue gas desulfurization life cycle costs are determined utilizing assumptions that are conservative in the sense that they minimize the cost differential between alternatives and base cases. The cost comparison shows that the alternative plant designs offer FGD cost saving from about zero to two percent.

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1. INTRODUCTION

The effectiveness, cost, and health effects of various levels of sulfur dioxide (SO_2) controls are important issues to determine. Techniques used in previous such studies assume that SO_2 emission rates from the facility under investigation are constant with time, or perhaps vary with plant operating characteristics (Department of Energy, 1980). These emissions are then used as input for atmospheric dispersion models, which predict SO_2 concentrations resulting from the facility's design emissions. Facilities subject to review under the Clean Air Act must also use this approach in projecting air quality effects of proposed facilities. Best Available Control Technology (BACT) is determined on a case-by-case basis, and electric utility plants are also subject to specified SO_2 removal requirements under New Source Performance Standards (NSPS). Such regulations do not assume that variability in fuel sulfur content exists, and the predicted ground-level SO_2 concentrations are expressed as a definitive number. These projected SO_2 concentration values are then compared to regulated values. If the projected concentration is less than the regulatory limit, the facility is acceptable from an air quality standpoint. If the projected values exceed these limits, the facility is unacceptable.

In reality, SO_2 emission rates are not constant in time or with plant load, but fluctuate as a result of the variability in the composition of the fuel used, and of the plant operating procedures (Warholic et al., 1980). Although present regulations do not specifically account for sulfur variability, and compliance with regulated limits is construed to mean that no violations will occur, a finite probability of exceeding either an emission limitation, a ground-level concentration limit, or both, exists. To reduce the potential for such violations due to unavoidable variations in emissions caused by nonuniform sulfur content in fuels, facilities typically purchase and consume a fuel that could average approximately 80% of the emissions that regulatory limits would allow. This subjective approach results in differences between assumed and actual SO_2 emissions, results in inaccurate air quality impact assessments, and

may not reduce the probability of an emission or ambient level violation to an acceptable level. Given the statistics of the variability in SO_2 emission rates and the meteorological conditions, it is possible to then calculate the statistics of the resulting ground-level SO_2 concentrations, and to predict the probability of exceeding some predetermined threshold values with a stochastic air quality model. This modified approach to air quality regulations, recently proposed by Witten et al. (1981), will improve the accuracy of estimates of air quality effects. The uniform application of such an approach will allow the operator of a facility to determine the fuel characteristics that will comply with the regulations, and thereby choose the base fuel and emission abatement devices that best suit the capabilities of each individual facility.

In this study, the air quality, health, and the economic benefits associated with various sulfur control options on a hypothetical coal-fired utility plant are analyzed using the stochastic approach. The analyses are done at a midwestern metropolitan area, where extensive demographic, meteorological, and ambient air quality data are available. This study, which is purely hypothetical, utilizes measured data for all inputs.

Reasonable SO_2 control options are determined for the facility. These options are chosen to represent presently available, state-of-the-art controls for both high- and low-sulfur coals, controls with a lack of the redundancy presently required of SO_2 control systems, and a facility with available controls and a taller stack than presently allowed. Such emission control options are not now available to a utility operator. BACT and NSPS requirements, due to their removal efficiency requirements, effectively preclude the use of systems where spare modules are not available. Such systems are too likely to suffer periods of high SO_2 emissions during equipment failure, which either results in regulatory violations or in the plant being shut down. However, the stochastic approach would allow such emission control options, provided that the predetermined limits on the mean and variability in the SO_2 emission rate are met. Also, the tall stack option, often used by utilities before 1977, is expressly forbidden by present regulations. This exclusion is designed to

reduce the long-range transport of SO_2 downwind of a facility. Current techniques for estimating regional SO_2 transport incorporate average SO_2 emission rates, with short-term fluctuations ignored (Shannon, 1981). Also, the effects of an elevated stack on regional concentrations are unknown, but tall stacks are effective in reducing short-term concentrations in the near vicinity of a facility. Therefore, the tall stack option is analyzed in this study with strongly reduced mean SO_2 emissions, which should serve to reduce the regional and national impacts of the facility, while the increased height of the stack will effectively reduce the maximum local short-term ground-level SO_2 concentrations. The tall stack option is analyzed in this study because mean SO_2 emissions are reduced by the alternative strategies, which could reduce the quantity of SO_2 available for long-range transport, and because the tall stack will effectively reduce maximum short-term SO_2 concentrations. These options span the range of emission scenarios that represent likely allowable levels of SO_2 controls. For each control strategy, the costs of purchasing, operating, and maintaining the equipment are evaluated.

For each control option, the effects on ground-level SO_2 concentrations are assessed for a single isolated source and multiple sources sited within the study area. Presently measured ambient SO_2 levels are used to determine the site-specific increment of increased SO_2 concentrations available before air quality regulations are exceeded. The probability of exceeding this available increment at each receptor in the study area is then calculated. In addition, the probability of exceeding the increment more than once, which would represent a violation of present regulations (Clean Air Act Amendments of 1977, PL 95-95, August 7, 1977), is calculated. A comparison of the projected effects for each control alternative is then made.

Along with events defined by regulatory requirements, probabilities of events associated with health effects are considered. Short-term levels of SO_2 other than the present regulatory limit may produce demonstrable health effects (Walsh, et al., 1982). The incrementable increase above ambient concentrations required to reach such levels is determined, and the probability of exceeding these health-related threshold values is calculated

for each control alternative. Using the demographic data available, the health risks associated with the projected population exposures for each control option are presented.

This hypothetical study provides a method for evaluating the true air quality, health, and economic costs and benefits associated with various sulfur control options. By modifications to present emission limitation and ambient SO₂ concentration regulations, the approach used in this study would be applicable to the analysis of the potential effects of any large SO₂-emitting facility, and would assist in more reasonably evaluating the alternatives available to a facility operator.

2. ANALYSIS OF POWER PLANT DATA

The variability in sulfur dioxide (SO_2) emissions has important ramifications for compliance of coal-fired utility boilers with federal and state air pollution regulations. Highly variable SO_2 emissions are more likely to cause one or more violations of an air quality standard than are emissions that are highly clustered about the mean (i.e., that have low variability). A wide variety of factors contribute to the variability of SO_2 emissions. The variability of sulfur in the coal before it is mined (in situ coal), the levels of ash and moisture in the coal, the methods of coal extraction and transportation, the sources (i.e., mines or seams within a mine) of coal for a particular power plant, the manner in which coal is stored and removed from storage at the power plant, the rate of coal consumption, the combustion process, and the type of SO_2 emission control equipment used at the power plant are all factors that can influence the variability of SO_2 emissions.

This study is concerned with an alternative approach to air quality regulation, namely, a stochastic approach that more realistically addresses the variability of SO_2 emissions than current regulatory schemes. Three aspects of SO_2 emissions that are of interest in developing a stochastic approach to air quality regulations are the variability of the emissions, the statistical distribution of the emissions, and the extent to which the emissions are autocorrelated. This section discusses each of these aspects in the context of statistical and time series analyses of SO_2 emissions data from power plants.

A lack of extensive and continuous SO_2 emissions data bases limited the number of power plants that could be analyzed in this study; for example, only two data bases were located that contained more than one month of continuous 24 hour average SO_2 readings. In some cases, statistical results obtained by other researchers were used for comparison purposes because insufficient data were available for analyses with the techniques used in this study. For example, curve fitting and time series analyses provide more meaningful results on large data bases, and were not attempted for smaller data sets.

The variability of SO₂ levels in stack gases (prior to passing through FGD devices) is strongly related to the variability of sulfur in coal as it is fed to the boiler. Unfortunately, the sulfur content of coal typically is not monitored as the coal is fed to the boiler; rather, it is measured as the coal is delivered to the power plant, since sulfur content is one of the characteristics of coal that affects its price (Miranda, 1981). The distribution of the sulfur content of coal as it is fed to the boiler must therefore be inferred from coal sulfur measurements made on coal as delivered, which in turn is related to the distribution of sulfur in the in-situ coal.

The sulfur content of in-situ coal in the United States typically ranges from less than 1% to about 7% (Andria, 1981). Sulfur content in coal can vary on a variety of geographic levels, such as region to region, mine to mine, seam to seam, and even within the same seam. Of greatest interest are variations in sulfur content observed in coal from a particular mine because of long term contractual agreements under which the output of a single mine is tied to a single user such as a power plant (ICF, 1980). Geologic factors such as the following determine the variability of sulfur in coal in the ground (Warholic, et al., 1980): the mode of accumulation and burial of coal forming vegetal matter; the structure and chemical composition of coal-forming vegetal matter; the extent of inert material washed into swampy areas at the time the coal-forming material was accumulated; the age and geographic location of the coal deposit; and the subsequent geologic history of the coal deposit, such as permeation of groundwater. Recent research at the United States Geologic Survey has found that in general, low (<4.0) pH during the peat stage of coal formation leads to coals that are both low in ash (<4%) and low in sulfur (<1%). As pH increases (4-7+) during the peat stage both the ash and sulfur contents may increase (Miranda, 1981). Because of these geologic factors the distribution of sulfur in coal in the ground is not completely random, i.e., there is a certain structure to the sulfur in coal deposits.*

*The distribution of in-situ coal sulfur is best characterized using tools in the field of geostatistics (Miranda, 1981; Kilgrove, 1981). Because a detailed discussion of geostatistical analysis of in situ coal sulfur is beyond the scope of this report the reader is referred to Journel and Huijbregts (1978) for more information.

Mining operations transform the spatial characteristics of coal sulfur into a time series. Alternative mining approaches within the same seam can produce different time series of sulfur in coal (and therefore different time series of SO_2 emissions). These series in turn will be modified by coal preparation, coal transportation, blending, and other factors. A study conducted by Rockwell, et al. (1975) of the coal use at the Navajo Generating Station in Page, Arizona (from the Kayenta Mine) found that the variance in the distribution of sulfur in coal is reduced by about a factor of eleven between mining the coal and using it as a fuel. Computer analysis of the sulfur distribution data found that about 80% of this reduction in variability can be attributed to the large volume of coal consumed by the Navajo Generating Station in any three hour period (2750 tons); i.e., a large fraction of the mine-core sulfur distribution is sampled in any given three hour period. The remaining 20% reduction in variability is attributed to diffusional mixing and coal handling operations, each of which contributes about 10% (Rockwell, et al., 1975).

Once coal is delivered to a power plant, its sulfur distribution has been considerably changed from that which existed in the in situ coal. The distribution of sulfur in coal as delivered is of most interest for this study because it represents the coal sulfur distribution located closest in time to the distribution actually fed to the boiler for combustion. Quantitative analyses of the distribution of sulfur in coal are beyond the scope of this document and are reported elsewhere for a variety of coals and power plants (Warholic, 1980; Miranda, 1981). For the purposes of this study it is sufficient to characterize the distribution of the sulfur in coal delivered to one of the power plants selected for SO_2 emissions analysis. Agreement of the distribution with that found by other researchers suggests that the distribution of SO_2 emissions from the power plant of interest would not be unduly influenced by anomalies in the coal sulfur data.

Figure 2.1 presents a histogram of coal sulfur measurements of coal as received at the Louisville Gas and Electric Company Cane Run No. 6 power plant during 1980. The data illustrate a log normal distribution in that the right hand tail of the distribution drops off more slowly than the left hand tail. This finding is in agreement with other studies of

Fig. 2.1. Histogram of sulfur in coal as received at Cane Run No. 6, 1980.

coal sulfur distribution. PEDCo (1977) found in a study of sulfur variability in low sulfur coals from selected mines that distributions of weight percent sulfur tend to be skewed to the right. Warholic, et al. (1980) analyzed coal sulfur data from over 1200 mines and concluded that values of weight percent sulfur were not normally distributed. For fitting the overall distribution, the inverted gamma distribution was considered to be slightly superior to the lognormal distribution. They also focused on fitting the upper tail of the distribution because high sulfur values represent potential exceedances of the SO_2 emissions standard. In the upper tail of the distribution no clear cut preference between the lognormal and inverted gamma distributions was observed to exist (Warholic, et al., 1980). It was thus concluded that few anomalies exist in the coal sulfur data.

In a non-strike situation, the variability of the sulfur content of coal supplied to a plant with a dedicated mine will closely follow the variability of sulfur in the in situ coal, which in turn could be estimated (using geostatistics) from an isopach sulfur map of the mine; however, as concluded by Warholic et al. (1980), the short term variability of sulfur in coal from an individual mine cannot be accurately predicted even if substantial historical data are available. Inferring SO_2 emissions variability from coal sulfur variability would thus be difficult at best.

The combustion process introduces variability into SO_2 emissions because the percentage of sulfur in feed coal converted to SO_2 is not consistent for all boilers and all coals. Typically, it is assumed in emissions calculations that 95% of feed coal sulfur is converted to SO_2 (the remainder is trapped in the ash or oxidized to sulfur trioxide). In reality, the percentage of S to SO_2 conversion can vary. A study done for the EPA found that seven power plants burning western coal emitted an average of 79.8% of the feed coal sulfur as SO_2 ; the range was 69.6 to 97.5%. For eastern coal, six power plants emitted an average of 90.4% sulfur with a range of 85.5 to 95.0%. These data suggest that western coals (subbituminous and lignite) may retain a greater proportion of the sulfur in the ash (KVB, 1978). Sulfur dioxide emissions variability may thus be tied to other coal constituents that affect the combustion

process. In theory, the variability of SO_2 emissions could be influenced by other constituents of coal as follows:

- o Ash--sulfur is retained in ash when it reacts with calcium, sodium, and potassium components of the ash; thus the ash can reduce the magnitude of the SO_2 emissions, and could influence the variability;
- o Moisture--water in coal effectively lowers the Btu/lb value of the coal, because part of the coal's energy is used to evaporate water rather than produce steam; thus, the coal feed rate could be increased, and SO_2 variability could be lowered;
- o Btu/lb--the amount of energy per pound of coal determines the coal feed rate of that the boiler needs to meet its generating demands; a low Btu/lb value could require large amounts of coal to be burned, which in turn could decrease the variability of the SO_2 emissions.

The effects of these constituents on SO_2 variability were not statistically analyzed in this study, mainly because they are not expected to be capable of significantly influencing the variability of SO_2 .

The variability of SO_2 emissions was studied using data bases compiled from SO_2 emissions monitoring data collected at a variety of utility and industrial boilers. Data collected at two Louisville Gas and Electric Company power plants (Cane Run No. 4 and Cane Run No. 6) were the most extensive, and thus were analyzed in most detail. Cane Run 4 data were obtained from the EPA (Kelly and Sedman, 1978) and Cane Run 6 data were obtained from Bechtel National Inc. (Watson, 1980). Statistical analyses of other data bases as presented in various reports were also used for comparison purposes.

A variety of statistical analyses were performed on the data (e.g., Fourier transform, power spectral density, logarithmic fit, autocorrelation, etc.), but only the analyses of most interest will be summarized here. The characteristics of the emissions data that are of most interest are:

- o the time sequence and distribution of SO_2 emissions before and after FGD systems;
- o the mean and standard deviation of SO_2 levels coming out of FGD systems;
- o the extent to which the SO_2 emissions coming out of the FGD systems are autocorrelated.

The purpose of comparing SO₂ emissions before and after FGD systems is to determine the effect of FGD systems on SO₂ emissions variability. Figures 2.2 and 2.3, respectively, present plots of inlet and outlet SO₂ levels (ppm) vs time (seconds) for the south unit of Cane Run 4 for data taken every 15 minutes over the period October 27, 1977 through December 5, 1977, respectively. By inspection of the plots, the outlet data (SO₂ levels after the FGD system) appear to have greater variability than the inlet data (SO₂ emissions before the FGD system). For the inlet data, the standard deviation is about 9% of the mean, whereas for the outlet data the standard deviation is about 50% of the mean. Smoothing these data by taking running 24-hour average SO₂ levels illustrated the same effect. Similar results were obtained for the Cane Run 6 data. These findings are in agreement with other studies of SO₂ emissions from boilers equipped with FGD units (ICF, 1980; Miranda, 1981).

The distributions of SO₂ levels before and after passing through a FGD unit are also of interest. Figures 2.4 and 2.5 present cumulative distribution functions for running 24 hour average SO₂ emissions data Cane Run 4 south inlet and outlet, respectively; the x's on the figures denote the actual data points, and the lines represent the best fit of a lognormal distribution to the data using equation (2.1):

$$y = 0.5 (1 + \text{ERF} (A \text{ LOG } (x) - B)) \quad (2.1)$$

where A and B are empirically determined coefficients and x and y are the abscissa and ordinate on the plot, respectively. The fact that the logarithmic curves fit the data well suggests that the data are lognormally distributed. The FGD unit appears to modify the distribution; i.e., the lognormal distribution, while providing an adequate fit, does not fit the outlet data as well as the inlet data. Similar results were obtained using the Cane Run 6 data, and other studies have also found lognormal distributions in SO₂ emissions (Miranda, 1981; Rockwell, et al., 1975). Thus it was assumed for this study that SO₂ emissions are lognormally distributed.

Given the fact that the distribution has been identified, it was next of interest to characterize the statistical mean and standard deviation of the distributions of SO₂ emissions at the FGD outlet. These two

Fig. 2.2. 15-minute SO₂ levels (ppm) from Boiler vs. time (10⁵ seconds) at Cane Run No. 4, south unit, 1977.

Fig. 2.3. 15-minute SO₂ emissions (ppm) from FGD unit vs. time (10⁵ seconds) at Cane Run No. 4, south unit, 1977.

Fig. 2.4. Cumulative distribution function (x's) of and lognormal curve fit (line) to 24-hour running average SO_2 levels from South boiler at Cane Run No. 4, 1977.

Fig. 2.5. Cumulative distribution function (x's) of and lognormal curve fit (line) to 24-hour running average SO₂ emissions (ppm) from South unit at Cane Run No. 4, 1977.

parameters are used as input to the stochastic air quality models. The mean and standard deviation were calculated from a log normal curve fit of the distributions of the Cane Run 6 and Cane Run 4 data bases using equation 2.1. The mean (ME) and standard deviation (SD) were calculated from the values obtained from the curve fit using the following expressions:

$$ME = e^m + \sigma^2/2; \quad SD = e^m + \sigma^2/2 \sqrt{e^{\sigma^2} - 1} ;$$

the value of m is equivalent to the value of "B" from the curve fit, and the value of σ is equal to $1/A\sqrt{2}$ from the curve fit (equation 2.1). The purpose of calculating σ and m , in addition to providing input to the air quality model, is to evaluate the variability of the SO₂ emissions data bases. The coefficient of variation (also called standard error or relative standard deviation), which is calculated by dividing SD by ME and multiplying the quotient by 100%, is used to compare the variabilities of the data bases. Table 2-1 presents the coefficients of variation for Cane Run 4 and Cane Run 6; coefficients of variation for other power plants, based on the arithmetic mean and standard deviation (since insufficient data were available for a curve fit) are also presented for comparison. Coefficients of variation based on the curve fit were calculated by finding the value of $\sqrt{e^{\sigma^2}-1}$, since this expression is equivalent to the ratio of SD/ME. Pertinent data describing each power plant are included. Coefficients of variation ranged from 15%, indicating a high degree of clustering about the mean, (and hence little variability) to a high of 44%, indicating considerable variability in the data. The average coefficient of variation was 32%.

Intuitively, one would not expect a high degree of similarity among coefficients of variation of SO₂ emissions from different boilers because FGD systems are operated to meet different criteria (e.g., minimizing operating costs while maintaining SO₂ removal efficiencies within a certain range). In other words, much of the observed variability could be operator induced, and there is no reason to expect that all FGD systems will be operated alike.

The last item to be discussed in this section is an examination of the extent to which SO₂ emissions are autocorrelated. If SO₂

Table 2-1. Summary of coefficients of variation of 24-hr average SO₂ emissions from selected power plants

Power Plant Name*	Gross Generating Capacity (MW)	FGD System	Design Removal Efficiency (%)	Coefficient of Variation (%)	
				Arithmetic	Curve Fit
Cane Run 4 N, LGEC	188	Carbide Lime	85.0	27.4	32.0
Cane Run 4 S, LGEC		Carbide Lime	85.0	44.2	34.0
Cane Run 6, LGEC	288	Dual Alkali	95.0	35.4	26.5
Bruce Mansfield Set 1, PPC	917	Lime	92.1	26.3	**
Bruce Mansfield Set 2, PPC	917	Lime	92.1	22.2	**
Eddystone No.1, PEC	120	Magnesium Oxide	90.0	41.2	**
Mitchell No. 11, NIPSCO	115	Wellman Lord	90.0	15.0	**
Rickenbacker ANGB	61.5	Limestone w/ Adipic Acid	90-95	41.3	**
Conesville, CSO	411	Lime	89.5	33.0	**
Shawnee, TVA	10	Lime	N/A	25.0	**
Shawnee, TVA	10	Lime w/Adipic Acid	N/A	44.0	**

*LGEC = Louisville Gas and Electric Company (Louisville, Kentucky)
 PPC = Pennsylvania Power Company (Shippingport, Pennsylvania)
 PEC = Philadelphia Electric Company (Philadelphia, Pennsylvania)
 NIPSCO = Northern Indiana Public Service Company (Gary, Indiana)
 ANGB = Air National Guard Base (Columbus, Ohio); industrial boilers used for space heating
 CSO = Columbus and Southern Ohio (Conesville, Ohio)
 TVA = Tennessee Valley Authority (Paducah, Kentucky)
 ** Insufficient data for regression analysis
 SO₂ emissions from same scrubber at two different time periods
 N/A Not available

Source:

Conesville and Shawnee data obtained from ICF, 1980.

Rickenbacher data obtained from Clarke, et al., 1981.

Cane Run 6 data obtained from Watson, 1980.

All other data obtained from Kelly and Sedman, 1978.

emissions are uncorrelated over time, then the high and low values will tend to cancel out, and the variability in SO₂ emissions will be decreased because of averaging. On the other hand, if SO₂ emissions are perfectly correlated, then one day's average SO₂ level is a good predictor of the next day's, and the variability in SO₂ emissions will not necessarily be decreased by averaging. Under such conditions, the fluctuations in SO₂ levels could result in exceedances of the emissions standard.

Figure 2.6 presents a plot of autocorrelation coefficient (ranging from 0 to 1, with the latter indicating a high degree of autocorrelation) vs lag time (in seconds $\times 10^6$) for 24-hour average SO₂ emissions from the FGD unit at Cane Run No. 4. The variation of the autocorrelation coefficient with time follows a pseudo-exponential decay. The fact that the autocorrelation coefficient does not go below 0.8 suggests that SO₂ levels can be autocorrelated over long time periods. Figure 2.7 presents an autocorrelation plot for the Cane Run 6 data, reflecting a similar pattern to the Cane Run 4 data.

By assuming that these plots follow an exponential decay, the time over which the SO₂ levels are autocorrelated can be estimated by calculating the e-folding time of the autocorrelation coefficient. The e-folding time is defined as the time required for the autocorrelation coefficient to decay to 1/e of its original value. The autocorrelation e-folding time, τ , can be estimated using the following equation:

$$\text{autocorrelation} = e^{-t/\tau}$$

where t is the time at which the autocorrelation was observed. The Cane Run 4 data exhibit an autocorrelation e-folding time of about 40 to 50 days, and the Cane Run 6 data exhibit an e-folding time of about 80-90 days. These results suggest that SO₂ emissions are highly autocorrelated over long time periods, and that the assumption of perfect autocorrelation over typical time periods represented by emissions and ambient air quality standards is valid.

The results of this section can be summarized as follows

- o the variability of in situ coal sulfur can be greater than that it found in as received coal;

Fig. 2.6. Autocorrelation vs lag time (10^6 sec) for SO_2 emissions from FGD unit at Cane Run No. 6, 1980.

Fig. 2.7. Autocorrelation vs lag time (10^5 sec) for SO_2 emissions from FGD unit at Cane Run No. 4, 1977.

- o SO₂ emissions are approximately lognormally distributed;
- o SO₂ emissions from boilers equipped with FGD systems can exhibit a wide degree of variability;
- o SO₂ emissions can be highly autocorrelated over long time periods.

These results will be used in the next section to formulate power plant emissions scenarios and in following sections to conduct air quality analyses of the emissions scenarios.

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3. PLANT DESIGN SCENARIOS

The objective of this section is to develop cost effective plant scenarios which would utilize the flexibility inherent in a stochastic approach and which would not be allowed under existing regulations. Perhaps the greatest advantage of the stochastic approach is greater flexibility which would be allowed during process upset conditions. Current regulations require normal plant shut-down during major flue gas desulfurization (FGD) systems failure. To avoid such situations, utilities typically install reserve sulfur dioxide removal capacity. Typical scrubber "sparing" ranges from 25% to 33%, i.e., five-25% capacity modules or four-33% capacity modules. The investigation of plant design scenarios, for the most part, is concerned with more cost-effective options for dealing with upset conditions.

The stochastic approach assumes that power plant sulfur dioxide emissions are governed by a probability distribution. The data analysis of the previous section suggests that these emissions are lognormally distributed. This section will consider the changes in emission distribution that will result from the modification of plant design and plant operation which minimize or eliminate SO₂ removal redundancy. Section 4 will address the air quality impacts of these emission scenarios and Section 7 will quantify, to the extent possible, the associated health effects.

The emissions distribution can be represented by its mean and standard deviation. Maintaining the usual plant design while eliminating the flue gas desulfurization sparing will result in both an increased mean emission rate and an increased emission rate standard deviation which will in turn cause increased air quality impacts and possible increased health effects. Such an approach is inconsistent with the mission of this study which is to identify alternative plant scenarios that will offer cost advantages to utilities while keeping air quality and health effects at, or below those allowed under the existing air quality regulations. Therefore a concept of emissions banking is introduced. This concept requires that every episode in which emissions exceed those currently allowed be balanced by many

episodes of greatly reduced emissions. In terms of the emission rate probability distribution, the higher emission rate standard deviation which results from emissions allowed during FGD system upsets must be offset by a reduced mean emission rate.

A plant designed to be in compliance with existing air quality regulations (base case) is developed for both a plant sited in the eastern United States burning a high-sulfur eastern coal and a plant sited in the western United States burning a low-sulfur western coal. Alternative plant scenarios are investigated for both the eastern plant and western plant. In this study all power plants are assumed to have a gross rating of 500 MWe and utilize a typical pulverized coal combustor. The eastern plant scenarios are assumed to use a southeastern Ohio Pittsburg seam bituminous coal having a mean heating value of 11,500 Btu/lb and a mean sulfur content of 3.35% by weight before beneficiation. The western plant scenarios are assumed to use a Wyoming subbituminous coal having a mean heating value of 9000 Btu/lb and mean sulfur content of 0.5% by weight. The sulfur removal strategy for the eastern base case is to remove 14% of the coal sulfur by beneficiation followed by an additional 87% removal through scrubbing providing a total sulfur removal capability of 89%. The FGD system for this plant consists of five-125MW capacity (four operating + one spare, 25% sparing), wet-lime scrubber modules. The eastern coal alternative plant design also utilizes cleaned coal. However, the design FGD removal efficiency is increased to 93% while no sparing is provided (four-125 MW scrubber modules). The greater removal efficiency is required to, in part, offset greater emissions which could occur during upsets since no backup is available. When all four modules are fully operative an overall sulfur removal (including beneficiation) of 94% will be realized. Plant sulfur dioxide emission rates estimated for the base case assumes that, with the sparing, an FGD removal efficiency of 87% will be available at all times. For the alternative plant design, emission rates are estimated assuming that all four modules are available 85% of the time, only three modules are available 10% of the time, and only two modules are available 5% of the time. This is equivalent to a "down time" for each module of approximately 2.5 weeks per year. Under these conditions no excessively large emissions will occur since the minimum

total sulfur removal efficiency (beneficiation + FGD) is 54% and the mean total removal efficiency over the course of one year is 90%.

The sulfur removal strategy for the western base case assumes a continuous FGD removal efficiency of 70% utilizing five-125 MW capacity dry scrubber modules (four operating + one spare). Beneficiation is not considered for the western coal scenarios since it is typically not effective on subbituminous coals. The western coal alternative scenario involves no sparing and utilizes four-125 MW capacity dry scrubber modules having design removal efficiencies of 80%. As in the eastern coal alternative, it is assumed that all four modules are available 85% of the time, only three modules are available 10% of the time, and only two modules are available 5% of the time. No excessively large emission rate will occur for this scenario since the minimum sulfur dioxide removal efficiency is 40%. The mean removal efficiency for the western alternative scenario is 76%.

Mean sulfur dioxide emission rates and emission rate standard deviations are developed with the assumptions described above along with the assumption that the emission rate coefficient of variation is 0.4 (a standard deviation equal to 40% of the mean). This value lies in the high part of the range presented in Section 2. Exceedance and violation probabilities are quite sensitive to the standard deviation and the large coefficient of variation was selected since it represents a conservative assumption with respect to air quality impacts and health effects. The emission rate means and standard deviations used in this study are as follows:

	Mean (g/s)	Standard deviation (g/s)
eastern base case	382	153
eastern alternative	343	401
western base case	205	82
western alternative	164	100

The emission rate probability distributions for the eastern scenarios and the western scenarios are shown in Figure 3.1 and 3.2, respectively. These figures clearly show the effect of decreasing the mean emission rate

EASTERN SCENARIO

Fig. 3.1. Emission rate probability distribution for the eastern base case (solid line) and the eastern alternative (dotted line).

WESTERN SCENARIO

Fig. 3.2. Emission rate probability distribution for the western base case (solid line) and the western alternative (dotted line).

and increasing the standard deviation, with respect to the base cases, on the emission rate probability distribution. The banking concept for dealing with FGD upset conditions becomes evident by finding the relative differences in area under certain portions of these curves. The eastern alternative produces greater emissions than the eastern base case 7% of the time which is offset by lower (banked) emissions 39% of the time. The western alternative shows higher emissions than the base case 2% of the time in contrast to lower emissions 51% of the time.

Table 3.1 provides pertinent plant design parameters for the four scenarios considered in this study. In all four cases, a stack height of 500 ft is shown. In the air quality analysis provided in Section 6 a taller stack is also considered as a measure to reduce the higher ground-level sulfur dioxide concentrations produced by the eastern alternative. For this "tall stack" option, a stack height of 900 ft is assumed.

Plant capital, operating, and maintenance costs are calculated utilizing relative costs given in the literature escalated to 1981 dollars and using a model developed by TRW, Inc. for the Department of Energy's Morgantown Energy Technology Center (Department of Energy, 1978). This model which is based upon an economic performance algorithm (TRW, 1979), was developed to perform cost comparisons between conventional pulverized coal combustors and atmospheric fluidized-bed combustors capable of utilizing FGD systems. The model computes costs beginning at mine mouth. Fuel requirements, sorbent requirements, and solid waste volumes given in Table 3.1 are computed using this model and conservatively assuming 7000 hours per year of plant operation. This model is also used to provide the capital costs of the FGD systems. The capital cost data base included in the model is based on 1979 dollars so the model results are scaled by a multiplier to escalate these values to 1981 dollars. This data base does not include dry scrubbers so the capital cost for the western scenarios provided by the model are adjusted based on a cost comparison between wet and dry scrubber systems performed by the Basin Electric Power Cooperative (Jannsen and Eriksen, 1979) for several western power plants. This study showed that the use of dry scrubbers results in capital cost savings of 11% to 18% over wet scrubber systems. Based on this finding, a multiplier

Table 3.1. Plant Design Parameters

	Eastern Scenarios		Western Scenarios	
	Base Case	Alternate	Base Case	Alternative
Gross Capacity (MW)	500	500	500	500
Coal Heating Value (Btu/lb)	11,500	11,500	9,000	9,000
Coal Sulfur Content (%)	3.35	3.35	0.5	0.5
Coal Utilization (tons/year)	1,465,674	1,465,674	1,930,400	1,930,400
Beneficiation (%) ¹	14	14	0	0
Scrubber Type	wet-lime	wet-lime	dry-lime	dry-lime
FGD Design Removal Efficiency (%)	87	93	70	80
Total Design Removal Efficiency (%)	89	94	70	80
Sparing (%)	25	0	25	0
Sorbent Requirement (tons/yr)	84,531 ²	85,658 ²	16,414 ³	17,821 ³
Solid Waste (tons/yr) ⁴	179,316	181,707	33,286	36,139
Stack Gas Temperature (ok)	352.4	352.4	352.4	352.4
Stack Height (m)	152.4	152.4	152.4	152.4
Stack Diameter (m)	6.0	6.0	6.0	6.0
Stack Gas Exit Velocity (m/s)	32.1	32.1	32.1	32.1
Mean SO ₂ Emission Rate (g/s)	382	343	205	164
Emission Rate Standard Deviation (g/s)	153	401	82	100

¹Based on lbs SO₂/MMBtu.

²Stoichiometric ratio of 1.1.

³Stoichiometric ratio of 1.2.

⁴Dry tons.

of 0.85 is used to adjust the dry scrubber capital cost predicted by the model. With this correction, predicted capital cost for the western base case is \$33,770 million and the predicted capital cost for the western alternative \$33,705 million. In order to check the accuracy of these predictions, Niro Atomizer, Inc., (a dry scrubber vendor), was contacted (Hansen, 1981) and was requested to independently develop capital cost estimates. Costs provided by Niro Atomizer are \$45 million and \$43 million (in 1982/1983 dollars) for the western base case and western alternative, respectively. This difference suggests that the model estimates for both the total capital cost and the relative cost differential between the two systems are conservative.

Annual sorbent costs and solid waste disposal costs are determined using the annual volumes provided in Table 3.1 assuming a lime cost of \$42 per ton for the eastern scenarios and \$62 per ton for western scenarios, and using a solid waste disposal cost of \$4 per ton for the eastern scenarios and \$2 per ton for the western scenarios. The increased cost of lime for the western scenarios is due to greater transportation costs while the lower solid waste disposal cost for the western scenarios is due to the assumption that the western plants are mine-mouth plants at which the solid waste is used in reclaiming the surface mine and thus no additional land is required. Annual power costs for the eastern scenarios are calculated based on a cost of 7.25 per MW per hour of operation of each scrubber module. Since most of the power required by the FGD system is used for fans to drive the flue gas through the scrubbers, power costs are assumed independent of the design sulfur dioxide removal efficiency. Jannsen and Eriksen (1979) have estimated that dry scrubbers offer a power saving of 25% to 50% as compared with wet scrubbers. As a result power costs for the western scenarios are derived in a similar manner to the eastern scenario but with a final cost multiplier of 0.67. Manpower costs are based on the findings of Jannsen and Eriksen (1979) for both wet and dry scrubbers. The eastern base case assumes a manpower requirement of 11 operators and 19 maintenance personnel. A lack of sparring will not likely reduce the number of FGD operators but would likely reduce the number of FGD maintenance personnel in proportion to the total number of scrubber modules.

Therefore, manpower requirements for the eastern alternative are assumed to be 11 operators and 16 maintenance. Similarly, the western base case assumes six operators and seven maintenance and the western alternative assumes six operators and six maintenance. For all cases, annual worker salaries are assumed to be \$35,000.

FGD systems capital costs and total operating and maintenance costs (based on 35 year plant life) for eastern scenarios and western scenarios are provided in Tables 3.2 and 3.3, respectively. These values are all in 1981 dollars and do not assume any cost escalation over time due to inflation. For the eastern scenarios, the alternative plant design shows a relative cost saving of about 2% compared to the base case, while for the western scenarios the cost of the alternative plant design is essentially the same as for the base case.

Table 3.2. Cost Comparison for Eastern Scenarios

	Base Case	Alternative
Capital Cost (10 ⁶ Dollars)	51.815 ¹	50.290 ²
O and M Costs ³ (10 ⁶ Dollars)		
Sorbent Cost	124.260	125.917
Sludge Disposal Cost	25.104	25.439
Power Cost	35.525	33.749
Manpower Cost	36.750	33.075
Total O and M Cost	221.639	218.180
Total FGD Cost	273.454	268.47

¹ 103.63 \$/KW

² 100.58 \$/KW

³ Based on a 35 year plant life

Table 3.3. Cost Comparison for Western Scenarios

	Base Case	Alternative
Capital Cost (10 ⁶ Dollars)	33.770 ¹	33.705 ²
O and M Costs ³ (10 ⁶ Dollars)		
Sorbent Cost	35.619	38.672
Sludge Disposal Cost	2.330	2.530
Power Cost	23.802	22.612
Manpower Cost	15.925	14.700
Total O and M Cost	77.676	78.514
Total FGD Cost	111.446	112.219

¹ 67.54 \$/KW.

² 67.41 \$/KW.

³ Based on a 35 year plant life.

Most of the cost components estimated here are highly site specific. As a result, the comparative costs could be expected to change significantly on a case by case basis. Additionally, several factors not included in this analysis may contribute greatly to the attractiveness of the alternative scenarios. First, the analysis does not consider the slight increase in power plant efficiency as a result of lack of FGD sparing. Second, and more important, the banking concept of the alternative scenarios offers utilities a more flexible means of dealing with upset situations and this is particularly important in load shifting. This factor alone could have a notable impact on electric rates. An additional factor not considered here, but discussed in greater detail in Section 5, is the manner in which utilities currently deal with emissions variability. Utilities recognize the variability and under certain circumstances reduce emissions by 15% to

20% to insure compliance with emission limits. If this "margin of safety" must be achieved by utilizing a coal with a sulfur content below the permissible maximum value, plant operating costs could increase. Such an increase in cost would be most significant if it resulted from an increased cost of coal transportation.

Other forms of emissions banking can be considered such as sparing with reduced removal efficiency for the reserve module. Any scenarios of this type are bounded in both cost and impacts by the scenarios analyzed in detail and consequently are not considered. A completely different approach would be to consider a scrubber with greater design removal efficiency but with a greater standard deviation. As discussed in Section 2, an FGD system acts as an amplifier of variations in flue gas sulfur dioxide content. FGD systems utilize control mechanisms to minimize this amplification. It is possible that a lower cost system could be manufactured if less sensitive control features are utilized. The investigation of the costs associated with such an FGD system are beyond the scope of this study.

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4. AIR QUALITY ANALYSIS

Single Source Analysis

The comparative impacts on air quality among the plant design scenarios described in the previous section are analyzed here. These analyses are performed with the plants located in a hypothetical urban/rural region having a population distribution shown in Figure 4.1. The blackened areas of this figure represent natural water bodies which are included as points of spatial reference for use in comparing results. Background ambient highest 24-hr averaged and annual averaged concentrations of sulfur dioxide assumed in this study are shown in Figures 4.2 and 4.3, respectively.

The air quality analyses focus on the probability of exceeding or violating (two or more exceedances) the 24 hr-average national primary ambient air quality standard (NAAQS) for sulfur dioxide of $365 \mu\text{g}/\text{m}^3$. The occurrence probabilities of events of interest (exceedances or violations) are calculated using the single source stochastic air quality model (Witten, et al., 1981) developed at Oak Ridge National Laboratory (ORNL). Requirements of this model are the mean emission rate and emission rate standard deviation as developed in Section 3. The model assumes that the emissions are perfectly correlated in time. This assumption is consistent with the long correlation times evident in the data analyzed in Section 2. A similar stochastic model developed for the Environmental Protection Agency (EPA) (Environmental Protection Agency, 1980) assumes that the plant emissions are uncorrelated in time. An analysis of the effects of correlation time on violation probabilities is given in Witten et al. (1982a). Based on this analysis, it appears that the model results are insensitive to correlation times for the range of violation probabilities predicted in this study. Therefore, it is anticipated that the use of the EPA model or any alternative model will not alter the outcome of this study.

The stochastic model statistically analyzes the results of an atmospheric dispersion model. The dispersion model used in this study is the EPA-developed CRSTER model (Environmental Protection Agency, 1977). CRSTER calculates ground-level pollutant concentrations at 10° angular

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POPULATION DISTRIBUTION

ORNL-DWG 81-23601

Fig. 4.1. Population density in study region.

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AMBIENT LEVELS OF SULFUR DIOXIDE (MICROGRAMS PER CUBIC METER)

ORNL-DWG 81-23600

Fig. 4.2. Ambient short-term (24-hr averaged) levels of sulfur dioxide in study region.

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ANNUAL ARITHMETIC MEAN SULFUR DIOXIDE CONCENTRATION (MICROGRAMS PER CUBIC METER)

Fig. 4.3. Ambient levels of annual-averaged sulfur dioxide concentrations in study region.

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intervals at up to five radial distances or rings. To achieve greater coverage of the region under investigation in this study, the model has been modified by ORNL to accommodate twenty rings. The ring configuration used for the model applications is shown in Figure 4.4. The plant location is at the center of these concentric rings. The modeled region is assumed to have no topographic variability so the CRSTER terrain option is not used. Five consecutive years of meteorological data taken at Minneapolis-St. Paul were examined in order to select a typical year (1975) and a worst-case year (1977) with respect to the possible violation of the 24-hr NAAQS. Results are provided for both of these years.

Violation probabilities are calculated using the spatially varying 24 hr ambient sulfur dioxide levels given in Figure 4.2. In all calculations, it is assumed that the second highest 24 hr-averaged ambient concentrations are equal to the highest ambient 24 hr concentrations. A violation occurs when the sum of the second highest 24-hr ambient concentration and the second highest incremental 24-hr plant induced concentration exceeds 365 micrograms per cubic meter. For all cases, the violation probabilities are too low (much less than 1%) to be of interest in this study. Probabilities of violating the full 24 hr PSD increment of 91 micrograms per cubic meter are also calculated. In this case the local standard is taken to be the minimum of 91 micrograms per cubic meter or the difference between 365 micrograms per cubic meter and the 24 hr ambient concentration. Again all violation probabilities are much less than 1%. This is a result of the relatively high incremental plant induced concentrations occurring at locations where ambient sulfur dioxide concentrations are relatively low. Therefore, the conservative assumption is made that both highest and second highest 24 hr averaged ambient sulfur dioxide concentrations do not vary with location and are equal everywhere in the region to the highest ambient concentration of 335 micrograms per cubic meter. This assumption may also be interpreted as the applicable State Implementation Plan allowing a given facility to consume no more than one-third of the full PSD increment. This constant ambient assumption is used for all the single source results presented in this study.

Fig. 4.4. Concentric rings used for the CRSTER model. The source is at the center of the rings.

Figures 4.5 through 4.8 show the spatial distributions of probabilities of one and only one exceedance (exceedance probability) and the probabilities of a violation (two or more exceedances) for the eastern coal plant scenarios. Exceedance probabilities for 1975 are shown in Figure 4.5. The base case plant design (5a) exhibits moderate exceedance probabilities over a small area while the alternative plant design (5b) exhibits greater exceedance probabilities over a larger portion of the region. Exceedance probabilities for 1977 are shown in Figure 4.6. Comparative results for the three cases are similar to the 1975 comparative results with the exceedance probabilities being slightly lower for each case. Figures 4.7 and 4.8 show violation probabilities for the two plant scenarios for 1975 and 1977, respectively. For all cases, violation probabilities are significantly less than exceedance probabilities. However, the relative effects of the different plant scenarios on the violation probabilities are similar to the exceedance probability results.

Along with probabilities of exceedances or violations at specified locations, the stochastic model also predicts the probability of observing an exceedance or violation anywhere in the modeled region. Table 4.1 presents the probability of observing one and only one exceedance and the probability of observing a violation of the 24 hr sulfur dioxide NAAQS anywhere in the study region. In addition, the maximum incremental (the amount which is added as a result of plant operations) annual average ground-level sulfur dioxide concentrations for the two eastern coal scenarios and the two western coal scenarios are given in Table 4.1. For the eastern coal plant scenarios, it can be seen that the "no-sparing" FGD configuration of the alternative design increases the exceedance probability from about 5% in the base case to almost 11% for 1975. Similarly the violation probability increases from less than 1% to more than 4% for 1975, and from less than 1% to about 5% for 1977. While the alternative plant design produces an increase in violation probability, it produces a decrease in the incremental annual average ground-level sulfur dioxide concentration. This decrease is approximately 10% for both 1975 and 1977,

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO BASE CASE
CONSTANT AMBIENT - 1975

ORNL-DWG 81-23612

Fig. 4.5a. Predicted probability of exceeding once and only once a total ground-level sulfur dioxide concentration of $365 \mu\text{g}/\text{m}^3$ for 1975 meteorological conditions for (a) eastern base case and (b) eastern alternative.

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO ALTERNATIVE
CONSTANT AMBIENT - 1975

ORNL-DWG 81-23605

Fig. 4.5b.

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO BASE CASE
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23603

Fig. 4.6a. Predicted probability of exceeding once and only once a total ground-level sulfur dioxide concentration of $365 \mu\text{g}/\text{m}^3$ for 1977 meteorological conditions for (a) eastern base case, and (b) eastern alternative.

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO ALTERNATIVE
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23606

Fig. 4.6b.

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VIOLATION PROBABILITY (%) EASTERN COAL SCENARIO BASE CASE CONSTANT AMBIENT - 1975

ORNL-DWG 81-23602

Fig. 4.7a. Predicted violation probability (two or more exceedances of $365 \mu\text{g}/\text{m}^3$ for 1975 meteorological conditions for (a) eastern base case, and (b) eastern alternative.

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VIOLATION PROBABILITY (%) EASTERN COAL SCENARIO ALTERNATIVE CONSTANT AMBIENT - 1975

ORNL-DWG 81-23608

Fig. 4.7b.

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VIOLETION PROBABILITY (%)
EASTERN COAL SCENARIO BASE CASE
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23604

Fig. 4.8a. Predicted violation probability (two or more exceedances of $365 \mu\text{g}/\text{m}^3$ for 1977 meteorological conditions for (a) eastern base case, and (b) eastern alternative.

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VIOLATION PROBABILITY (%) EASTERN COAL SCENARIO ALTERNATIVE CONSTANT AMBIENT - 1977

ORNL-DWG 81-23610

Fig. 4.8b.

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and is the result of the greater amount of sulfur dioxide removed in the alternative plant design. For both the base case and alternative the incremental ground-level annual average concentrations are small in comparison to the background concentrations (Figure 4.3).

Table 4.1. Summary air quality results

	Eastern Coal - 1975 (1977)		Western Coal - 1975 (1977)	
	Base Case	Alternative	Base Case	Alternative
Exceedance Probability (%)	5.06 (1.07)	10.99 (5.38)	0.06 (0.00)	0.26 (0.06)
Violation Probability (%)	0.15 (0.30)	4.15 (5.01)	0.00 (0.00)	0.01 (0.01)
Maximum Annual Average ($\mu\text{g}/\text{m}^3$)	0.52 (0.49)	0.47 (0.44)	0.28 (0.26)	0.22 (0.21)

Qualitatively, a similar comparison can be made for the western coal scenarios. However, as can be seen in Table 4.1, all probabilities are quite small. No spatial distribution plots, such as those in Figures 4.5 through 4.8, are provided since the violation and exceedance probabilities are too low to make such figures meaningful.

Thus far, exceedance and violation probabilities have been discussed. To obtain a more complete understanding of the relative differences in air quality impacts it is also necessary to consider ground-level sulfur dioxide concentration probability distributions and most probable number of exceedances of a standard. Figure 4.9 shows probability as a function of predicted 24 hr averaged incremental ground-level sulfur dioxide concentration at the points in space and time with the highest violation probabilities for the base case, and the alternative. The concept of emissions banking discussed in the previous section applies to ground-level concentrations as well. This figure shows that the alternative case peaks at smaller concentration values than the base case while exhibiting

Fig. 4.9. Probability vs. concentration for the eastern base case (solid line) and eastern alternative (dotted line) at the point in space and time where the second exceedance of $365 \mu\text{g}/\text{m}^3$ occurs.

a longer tail than the base case. Integrating under these curves reveals that the alternative plant scenario results in ground-level concentrations less than the base case plant scenario 38% of the time while causing higher concentrations 7% of the time. For the western coal, Figure 4.10, the alternative plant scenario results in ground-level concentrations lower than the base case 29% of the time and higher concentrations less than 1% of the time. As expected the increased removal efficiency of the alternative scenarios produces lower (banked) ground level concentrations during routine operating conditions which offset the higher (withdrawn) ground-level concentrations during the more frequent upset conditions.

It is difficult to compare a hypothetical stochastic air quality regulation with the existing air quality regulation since a stochastic approach must allow a finite violation probability while violations are prohibited (i.e., zero violation probability) under the existing regulations. In reality, the zero violation probability required under the existing regulations is never truly satisfied. The base case plant design is established to be in compliance with these regulations. Table 4.1 reveals that, although small, base case violation probabilities are not zero. The existing regulations allow one exceedance at any location during a one year period. A violation is any number of exceedances greater than one at a given location. An important comparison between a stochastic regulation and existing regulations is the change in total number of exceedances over time. The probabilities of 1 through 10 exceedances at each receptor location are calculated for both the eastern coal base case and the alternative for 1975. For each number of exceedances the maximum probability over all receptors is also found. These probabilities are used to construct Table 4.2 which shows maximum probabilities as a function of number of exceedances. The alternative plant scenario occurrence frequency for a violation is once in 24 years. Table 4.2 shows that this violation will most probably consist of two exceedances. The occurrence frequency for one exceedance is approximately twice in 24 years. This gives a total of three exceedances over 24 years. In comparison, the most probable number of exceedances over a 24 year period for the base case is one. Although the alternative scenario produces two more

WESTERN COAL SCENARIO 1975

Fig. 4.10. Probability vs. concentration for the western base case (solid line) and the western alternative (dotted line) at the point in space and time where the second exceedance of $365 \mu\text{g}/\text{m}^3$ occurs.

Table 4.2. Most Probable Number of Exceedances

No. of Exceedances	Probability (%)	
	Base Case ¹	Alternative ²
1	5.06	10.99
2	0.14	2.23
3	0.07	1.39
4	0.02	1.23
5	*	0.65
6	*	0.33
7	*	0.66
8	*	0.41
9	*	0.37
10	*	0.24

*Less than 0.01%.

¹Expected exceedances is 0.06.

²Expected exceedances is 0.43.

exceedances of the 24-hr NAAQS for sulfur dioxide over a 24 year period than the base case, the most probable number of total exceedances (three) is small when compared with the 24 exceedances in 24 years allowed under the existing regulations.

Multiple Source Analysis

Air quality analyses are performed for five identical coal-fired power plants located within the hypothetical study region. The locations of these facilities are shown in Figure 4.11. Exceedance and violation probabilities are calculated for the eastern coal scenarios using meteorological data from 1975 as input to the multi-source air quality model described in Witten et al. (1982b). Probabilities are calculated at the 130 receptor locations shown in Figure 4.12.

Figure 4.13 shows spatial distributions of violation probabilities for the five plants operating with the alternative design. For this model

SOURCE LOCATIONS

Fig. 4.11. Locations of the five power plant sites used in the multi-source analysis.

RECEPTOR LOCATIONS

Fig. 4.12. Receptor locations used in the multi-source analysis.

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VIOLETION PROBABILITY ALTERNATIVE VARIABLE AMBIENT

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Fig. 4.13. Spatial distribution of violation probabilities resulting from the operation of five facilities with the alternative plant design and assuming spatially variable ambient SO_2 concentrations.

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application, the air quality standard was allowed to vary with receptor location and was defined to be either the difference between the 24-hr NAAQS for SO_2 ($365 \mu\text{g}/\text{m}^3$) and local second highest 24-hr ground-level SO_2 concentration as given in Figure 4.2 or the full 24 hr PSD increment for SO_2 ($91 \mu\text{g}/\text{m}^3$), whichever is smaller. Although these results show greater violation probabilities than the single source results, they are still quite small, predicted to be 1% or less, and are too localized to be of interest in this study. A similar model run was made for all plants operating with the base case design. Violation probabilities at all receptors are at or near zero. Therefore, as in the single source air quality analysis, it is assumed that background SO_2 concentrations are spatially uniform and equal to $335 \mu\text{g}/\text{m}^3$ and the applicable 24 hr standard is then $30 \mu\text{g}/\text{m}^3$. Figure 4.14 shows the spatial distribution of violation probabilities for the five plants operating under the base case design. For the more stringent standard (constant ambient) the maximum violation probability has increased to more than 7%.

Exceedance and violation probabilities for the base case and alternative are provided in Table 4.3 for the eleven receptors exhibiting the greatest violation probabilities (based on base case results). Comparing violation probabilities between the base case and the alternative, it is observed that, in general, the alternative plant design results in greater violation probabilities than the base with the alternative having a maximum violation probability of more than 11% and the base case having a maximum violation probability of about 7%. A curious feature is evident at receptor 21 where the base case exhibits a greater violation probability (nearly 7%) than the alternative (less than 6%). This situation is, for the most part, a result of the individual sources being uncorrelated. Fluctuations in ground-level SO_2 concentrations resulting from fluctuations in emissions are reduced since some plants will exhibit emissions rates above the mean while other plants will exhibit emissions rates below the mean. Violation probabilities depend upon the mean emission rate and emission rate standard deviation. The consideration of multiple sources tends to reduce the relative importance of the standard deviation and to increase the importance of the mean emission rate. Since the base case

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VIOLATION PROBABILITY BASE CASE CONSTANT AMBIENT

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Fig. 4.14. Spatial distribution of violation probabilities resulting from the operation of five facilities with the base case plant design and assuming a constant available increment of $30 \mu\text{g}/\text{m}^3$.

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has a greater mean emission rate, the addition of sources will cause violation probabilities to increase more than for the alternative plant design. This fact becomes more apparent when comparing the single source results to the multi-source results. For the single source base case, the maximum violation probability (for 1975) is near 0% (Table 4.1), while for the multi-source result the maximum violation probability is more than 7%. The additional four sources have increased the base case violation probability by a factor of about 50. For the alternative plant design, the maximum violation probability is slightly in excess of 4% (Table 4.1) for a single source and more than 11% for the multiple sources. Here the additional four sources have increased the violation probability by only a factor of about three.

Table 4.3 Multi-Source Exceedance and Violation Probabilities

Receptor Number	One Exceedance base case/alternative	A Violation base case/alternative
6	2.44/5.90	6.80/9.88
7	0.04/2.16	6.73/7.57
12	6.38/8.09	6.87/11.51
13	1.96/4.82	6.87/10.46
14	0.39/2.65	7.25/11.06
20	0.01/1.97	6.73/7.09
21	0.56/6.25	6.73/5.43
30	0.13/3.02	4.09/7.96
32	0.16/1.19	7.00/10.83
63	0.24/3.53	4.44/9.97
93	0.03/2.84	5.41/5.78

These results suggest that for a sufficiently high density of sources, the alternative plant design would produce lesser violation probabilities than the base case. This hypothesis is investigated by

determining the violation probability at receptor number 63 as a result of the operation of 10 sources. Receptor 63 was selected because it exhibits the greatest ratio of alternative to base case violation probability for the five source results. The ten sources are located by doubling the number of sources at each source location shown in Figure 4.11. For ten sources, the base case violation probability is 80% while the alternative scenario violation probability is 71%. The addition of sources has resulted in the base case violation probability being greater than the alternative. Both violation probabilities are quite large due to the relatively small available increment of 30 g/m^3 . For a larger available increment of $37.5 \text{ } \mu\text{g/m}^3$, the base case violation probability becomes 42% and the alternative violation probability becomes 36%. A 25% increase in available increment has approximately halved the violation probabilities.

5. EMISSION LIMITS AND THE THIRTY DAY AVERAGING METHOD

Emissions from power plants are limited through restrictions imposed by State Implementation Plans (SIPs). Emission limits vary from state to state as well as varying within a given state or a given Air Quality Control Region (AQCR). For new sources, however, emission limits specified in SIPs must be at least as stringent as the Federal New Source Performance Standards (NSPS) which specify a level of SO₂ control that depends upon the sulfur content of the fuel, but with SO₂ emissions never to exceed 1.2 lbs/MMBtu. In Connecticut, for example, no new facility is allowed to consume more than two-thirds of the available PSD increment. The allowable emission limit is therefore the lesser of the emission rate which will meet the two-thirds PSD limit or NSPS. In New Jersey, identical existing coal burning facilities must comply with an emission limit which ranges for 0.3 lbs SO₂/MMBtu to 2.12 lbs SO₂/MMBtu depending upon where in the state the facility is sited.

Not only do emission limits vary, but techniques to determine compliance with these limits vary among states. For example, Oklahoma specifies 2 hr-averaged emissions as its measure of compliance, while many states, such as North Carolina, have SIPs with unspecified averaging periods. Recently, Indiana proposed to use 30 day rolling average emissions as a basis for establishing SIP emission limit enforcement priorities. Emission limit compliance based on a 30 day rolling average has generated considerable interest recently and this approach has been suggested as a possible regulatory change on a national basis. This extended averaging procedure is attractive to power plant operators since it offers them somewhat greater operating flexibility and serves to reduce the influence of emissions rate standard deviation (a parameter plant operators have minimal control over, Section II) on compliance. Critics of this approach believe that it will encourage plant operators to burn relatively low sulfur coal during part of a 30 day period to offset the burning of very high sulfur coal during another part of the same averaging period. This would result in episodes of decreased air quality.

In light of the attention given the 30 day rolling average, it is useful to quantify the effects of this approach on air quality. In order to do this, it is necessary to define some arbitrary measure of compliance. This is taken to be the probability of the 24 hr averaged emission rate exceeding an emission limit. For an emission rate which is lognormally distributed (Section 2) the probability of the emission rate exceeding a specified emission limit Y , can be written as

$$P_e(Y) = \frac{1}{2} \left\{ 1 - \operatorname{erf} \left[\frac{1}{\sqrt{2}\sigma} (\log(Y) - m) \right] \right\}, \quad (5.1)$$

where m and σ are related to the emission rate mean and standard deviation as given in Section 2. This measure has the advantage of explicitly accounting for the emission rate standard deviation, a significant parameter with respect to a rolling average procedure.

In meeting emission limits, plant operators account for emission variability by arbitrarily reducing the design emission rate in order to provide a margin of safety. This margin of safety is not rigorously established, but rather, is based on operating experience. The likelihood of exceeding an emission limit can never be eliminated; however, it can be reduced by increasing the margin of safety. Therefore, by selecting a margin of safety, a plant operator is implicitly establishing an acceptable level of risk (of exceeding an emission limit). For comparative purposes, an acceptable risk is arbitrarily taken to be a 0.1% probability of exceeding an emission limit (assumed to be 1.2 lbs SO_2/MMBtu) and with this the influence of emission averaging on this probability can be investigated.

An emission averaging procedure serves to reduce the emission rate standard deviation through the cancellation of variations above and below the mean emission rate which occur within the averaging period. A reduction in emission rate standard deviation will reduce the probability of exceeding a given emission limit (as defined by eq. (5.1)). For example, a power plant exhibiting a mean emission rate of 0.96 lbs SO_2/MMBtu and an emission rate standard deviation of 0.072 lbs SO_2/MMBtu (based on daily averaged values) will have a probability of exceeding 1.2 lbs SO_2/MMBtu of approximately 0.1%, the acceptable risk. A 10% increase or decrease in emission rate standard deviation will increase or decrease the

probability of exceeding the emission limit by a factor of three. In contrast, a 10% change in the mean emission rate will change the exceedance probability by a factor of 30. Since the averaging procedure will produce negligible changes in mean emission rate, changes in air quality which could result from a rolling 30 day averaging procedure can be quantified by investigating the change this procedure has on emission rate standard deviation.

Table 5.1 shows emission rate standard deviation and percent reduction in standard deviation as a function of increased averaging periods for three power plants. Data from Cane Run 4 are reported at fifteen minute intervals. A moving three hour (12 point) averaging is performed on these data and a mean and standard deviation are determined based on a best fit to a lognormal distribution (Section 2). Mean and standard deviations for the 24 hr and 30 day averaged data are determined in a similar manner. Cane Run 6 data are reported as daily averages. The means and standard deviations for 15 day and 30 day averaged data are determined using the same procedure applied to Cane Run 4. The standard deviations reported for the Mitchell plant are given by Warholic et al. (1980). For the power plants considered here, the percent reduction in standard deviation when going from 24 hr averaged data to 30 day averaged data ranges from 65% to 95%. This range reflects difference in time-wise autocorrelation for the different emission data sets. A data set which exhibits a strong autocorrelation implies, for example, that an emission rate which is greater than the mean at one instant in time will likely remain above the mean for a number of subsequent measurements. As a result, averaging these data will result in less cancellation of points occurring above and below the mean and, therefore, the averaging will produce a lesser reduction in the standard when compared with a data set exhibiting a lesser degree of autocorrelation. Therefore, the stronger the autocorrelation exhibited by a data set, the weaker the influence of averaging. To demonstrate this, consider the Cane Run 4 and 6 data sets. These data sets show autocorrelation e-fold times of 40-50 days and 80-90 days, respectively, and going from daily averaged data to data averaged over 30 days reduces the emission rate standard deviation by 65% and 66%

respectively. A random number generator is then used to produce sequences of numbers, lognormally distributed, having the same means and standard deviations as the two Cane Run units but with a zero autocorrelation e-folding time. Rolling 30 day averages are taken and new standard deviations are computed. For both data sets, the standard deviation was reduced by 82% as a result of the averaging procedure.

Table 5.1. Effect of Averaging Times on Variability
of SO₂ Emissions for Selected Power Plants

Power Plant/Averaging Period	Standard Deviation ³	Decrease in SD from Previous Value (%)
Cane Run 6 ¹		
24 hr	0.093	--
15 day moving	0.055	41
30 day moving	0.033	40
Mitchell ¹²		
3 hr moving	0.160	--
24 hr moving	0.109	32
30 day moving	0.005	95
Cane Run 4 ²		
3 hr moving	0.353	--
24 hr moving	0.286	19
30 day moving	0.098	66

¹Standard deviation computed from lognormal curve fit of distribution of data collected May 1, 1980 through September 18, 1980, as published in Watson, 1980.

²Source: Warholic et al., 1980.

³Units: lbs/SO₂/MMBtu.

Using equation (5.1), the change in exceedance probability resulting from the 30 day averaging procedure can be determined. Returning to the example facility with a mean emission rate of 0.96 lbs SO₂/MMBtu and a standard deviation of 0.072 lbs SO₂/MMBtu, a 65% reduction in standard deviation reduces the risk of violation from about 0.1% to about 10⁻¹⁵%. Greater reductions in emissions rate standard deviation will result in greater reduction in risk. It is clear that for this case, the 30 day rolling average has, in essence, eliminated the risk of violating the 1.2 lbs SO₂/MMBtu emission limit. The mean emission rate of 0.96 lbs SO₂ was selected to have an adequate margin of safety to achieve the assumed risk. As a result of the reduction in standard deviation produced by the 30 day averaging of emissions, the margin of safety could be reduced. If a plant operator is willing to accept the assumed risk of violation of 0.1%, a 65% reduction in emission rate standard deviation would allow the mean emission rate to be increased from 0.96 lbs SO₂/MMBtu to 1.12 lbs SO₂/MMBtu before the desired level of risk would be exceeded. For a 95% reduction in standard deviation, the mean emission rate could be increased to about 1.19 lbs SO₂/MMBtu. Since long term air quality is proportional to the mean emission rate, the increase in mean emission rate encouraged by the 30 day rolling average would increase the annual average ground-level SO₂ concentration from 17% to 24% for 65% and 95% reductions in emission rate standard deviation, respectively.

A method for comparing the 30 day rolling average emission limit to an emission limit based on daily averages is to determine the 24 hr based emission limit which would produce the same exceedance probability as that found for the 30 day averaged data with a limit of 1.2 lbs SO₂/MMBtu. Using the example facility having an emission rate mean and standard deviation of 0.96 lbs SO₂/MMBtu and 0.072 lbs SO₂/MMBtu respectively, the 65% reduction in standard deviation resulting from a 30 day rolling average on the Cane Run 6 data produces an exceedance probability which would equal the exceedance probability for daily averaged data based on an emission limit of 1.4 lbs SO₂/MMBtu. Similarly, for the Mitchell plant, the 95% reduction resulting from 30 day averaging is equivalent to an

increase of the daily averaged based emission limit from 1.2 lbs SO₂/MMBtu to 83 lbs SO₂/MMBtu. This increase may be unrealistically high since statistics for the Mitchell data are based on arithmetic calculations rather than best fits to a lognormal distribution. Perhaps a better example for data exhibiting weak correlation is the synthesized Cane Run 4 or 6 data which exhibit 82% reductions in standard deviation as a result of 30 day data averaging. For this case, the 30 day averaging is equivalent to increasing the daily averaged based emission limit from 1.2 lbs SO₂/MMBtu to about 3.5 lbs SO₂/MMBtu.

The results of the analysis presented here suggests that the implementation of emission limits based on 30 day rolling averaged data would offer plant operators greater flexibility by reducing the influence of emissions variability on compliance. However, this approach could also allow, if not encourage, a significant overall increase in SO₂ emissions. Additionally, this averaging procedure is highly sensitive to the time-wise correlation exhibited by emissions data. Since the data sets examined display a range of correlation times and since this correlation is likely to be a factor beyond the control of plant operators, enforcement based on 30 day averaged data must be considered a non-uniform measure of compliance with a specified emission limit.

An alternative measure of compliance is to establish an upper limit on the probability of daily-averaged data exceeding a specified emission limit. This approach would provide a plant operator with greater flexibility in that it would allow a facility to operate with any emission rate mean and standard deviation which results in an exceedance probability less than the specified value. This is illustrated graphically in Figure 5.1 which shows a compliance/ violation map based on 0.1%, 1%, 5%, and 10% allowable probabilities of exceeding 1.2 lbs SO₂/MMBtu. For example assuming a 0.1% limit on the exceedance probability, a facility could operate with any combination of mean and standard deviation which fall below the 0.1% line on Figure 5.1. Compliance with a such probabilistic standard could be measured by quarterly statistical audits of the daily averaged emission data. Since a shorter averaging time is used, compliance is far less sensitive to autocorrelation than the 30-day

EMISSION LIMIT COMPLIANCE MAP

ORNL-DWG 82-13929

Fig. 5.1. Emission limit compliance map base on allowable probabilities of 0.1%, 1.0%, 5.0%, and 10% of exceeding a 24-hr-averaged emission limit.

averaging procedure. With this method, the allowable exceedance probability could be carefully selected to allow increased operating flexibility but without encouraging increased SO₂ emissions.

6. ALTERNATIVES

In addition to emission control devices, three other approaches have been used to reduce local SO₂ concentrations. Intermittent controls, which are employed during poor meteorological conditions, load shifting, which is used during these same poor meteorological periods, and tall stacks, which emit SO₂ at much higher altitudes, have all been used to reduce local SO₂ concentrations. Intermittent controls require large areas for stockpiling low-sulfur coal for use during pollution episodes, or the capital expenditure for pollution control devices that will be employed on an as-needed basis, in addition to an episode-forecasting ability. Load shifting requires a grid of interconnected facilities spread over a large region so that plants not located in the area of the pollution episode can take up the slack caused by reducing the emissions of facilities located in the affected area. The tall stack option requires a large chimney to be built to reduce local ground-level SO₂ concentrations by increasing the dilution of the SO₂. All three alternative approaches are presently forbidden by the Clean Air Act. By virtue of the land requirements for intermittent control through fuel changing and the necessary grid size for load shifting, these options are considered too site- and utility-specific to be addressed in this study. Therefore, this section considers only the tall stack option.

Tall stacks are prohibited because a greater emission release height could increase long range transport and because emission control is an environmentally preferable method for minimizing ground-level pollutant concentrations. In this study, the tall stack option is used in conjunction with the eastern coal alternative plant design to mitigate episodes of higher ground-level SO₂ concentration which might occur during FGD system upsets. This plant design offers 10% lower SO₂ emissions than a plant designed in compliance with existing regulations (the base case). The relationship between release rate, release height and long range impacts is not well understood; however, the reduced emission rate provided by the alternative plant design may, at least in part, offset any increase in long range impacts resulting from the use of a taller stack. For these reasons,

the use of a taller stack as proposed here does not seriously contradict the intent of the prohibition.

Probabilities of exceeding and violating a fixed 24 hr SO₂ PSD increment of 30 µg/m³ are calculated for the alternative plant design with a taller stack for 1975 and 1977. Figures 6.1 through 6.4 show the spatial distributions of probabilities of one and only one exceedance (exceedance probability) and the probabilities of a violation (two or more exceedances) for the three eastern coal plant scenarios (base case, alternative plant design, and alternative with a tall stack). Exceedance probabilities for 1975 are shown in Figure 6.1. The alternative plant design utilizing a taller stack (1c) yields results between the base case and alternative. The exceedance probabilities for the "tall stack" option are moderate and comparable to the base case while the exceedance probabilities are predicted to extend over a greater area for the tall stack than the area predicted for the base case and a somewhat lesser area than the alternative with the shorter stack. Exceedance probabilities for 1977 are shown in Figure 6.2. Comparative results for the three cases are similar to the 1975 comparative results with the exceedance probabilities being slightly lower for each case. For both 1975 and 1977 results, the use of a taller stack serves to partially mitigate the events which contribute to highest ground-level concentrations. Figures 6.3 and 6.4 show violation probabilities for the three plant scenarios for 1975 and 1977, respectively. For all cases, violation probabilities are significantly less than exceedance probabilities. However, the relative effects of the different plant scenarios on the violation probabilities are similar to the exceedance probability results.

Along with probabilities of exceedances or violations at specified locations, the stochastic model also predicts probability of observing an exceedance or violation anywhere in the modeled region. Table 6.1 presents the probability of observing one and only one exceedance and the probability of observing a violation of the 24 hr sulfur dioxide NAAQS anywhere in the study region. In addition, the maximum incremental (the amount which is added as a result of plant operations) annual average ground-level SO₂ concentrations for the three eastern coal scenarios are given in Table 6.1.

EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO BASE CASE
CONSTANT AMBIENT - 1975

ORNL-DWG 81-23612

Fig. 6.1a. Predicted probability of exceeding once and only once a total ground-level sulfur dioxide concentration of $365 \mu\text{g}/\text{m}^3$ for 1975 meteorological conditions for (a) eastern base case, (b) eastern alternative, and (c) eastern alternative with a tall stack. (Figures 6.1a and 6.1b and the same as Fig. 4.5a and 4.5b.)

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO ALTERNATIVE
CONSTANT AMBIENT - 1975

ORNL-DWG 81-23605

Fig. 6.1b.

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO TALL STACK
CONSTANT AMBIENT - 1975

ORNL-DWG 81-23609

Fig. 6.1c.

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO BASE CASE
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23603

Fig. 6.2a. Predicted probability of exceeding once and only once a total ground-level sulfur dioxide concentration of $365 \mu\text{g}/\text{m}^3$ for 1977 meteorological conditions for (a) eastern base case, (b) eastern alternative, and (c) eastern alternative with a tall stack. (Figures 6.2a and 6.2b are the same as Figs. 4.6a and 4.6b.)

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO ALTERNATIVE
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23606

Fig. 6.2b.

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EXCEEDANCE PROBABILITY (%)
EASTERN COAL SCENARIO TALL STACK
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23611

Fig. 6.2c.

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VIOLETION PROBABILITY (%)
EASTERN COAL SCENARIO BASE CASE
CONSTANT AMBIENT - 1975

ORNL-DWG 81-23502

Fig. 6.3a. Predicted violation probability (two or more exceedances of $365 \mu\text{g}/\text{m}^3$ for 1975 meteorological conditions for (a) eastern base case, (b) eastern alternative, and (c) eastern alternative with a tall stack. (Figures 6.3a and 6.3b are the same as Figs. 4.7a and 4.7b.)

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VIOLATION PROBABILITY (%) EASTERN COAL SCENARIO ALTERNATIVE CONSTANT AMBIENT - 1975

ORNL-DWG 81-23608

Fig. 6.3b.

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VIOLETION PROBABILITY (%)
EASTERN COAL SCENARIO TALL STACK
CONSTANT AMBIENT - 1975

ORNL-DWG 81-23607

Fig. 6.3c.

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VIOLETION PROBABILITY (%)
EASTERN COAL SCENARIO BASE CASE
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23604

Fig. 6.4a. Predicted violation probability (two or more exceedances of $365 \mu\text{g}/\text{m}^3$ for 1977 meteorological conditions for (a) eastern base case, (b) eastern alternative, and (c) eastern alternative with a tall stack. (Figures 6.4a and 6.4b are the same as Figs. 4.8a and 4.8b.)

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VIOLETION PROBABILITY (%)
EASTERN COAL SCENARIO ALTERNATIVE
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23610

Fig. 6.4b.

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VIOLATION PROBABILITY (%)
EASTERN COAL SCENARIO TALL STACK
CONSTANT AMBIENT - 1977

ORNL-DWG 81-23613

Fig. 6.4c.

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Table 6.1. Summary air quality results and tall stack comparison

	Eastern Coal - 1975 (1977)		
	Base Case	Alternative	Tall Stack
Exceedance Probability (%)	5.06 (1.07)	10.99 (5.38)	3.48 (2.24)
Violation Probability (%)	0.15 (0.30)	4.15 (5.01)	2.34 (1.22)
Maximum Annual Average ($\mu\text{g}/\text{m}^3$)	0.52 (0.49)	0.47 (0.44)	0.26 (0.22)

The effectiveness of the taller stack as a mitigative measure for the relatively higher episodes inherent in the alternative design can be seen in this table. With the tall stack, the exceedance probability is reduced to a value below the base case for 1975 and the violation probability is reduced from about 4% to slightly over 2% for 1975, and from 5% to about 1% for 1977. The tall stack also serves to further decrease the annual averaged incremental ground-level concentration resulting from the alternative plant design. The alternative plant design with a tall stack produces a maximum annual averaged incremental SO_2 concentration which is half of that produced by the base case.

The effect of the tall stack option on the ground-level concentration probability distribution is shown in Figure 6.5. This figure shows probability as a function of predicted 24 hr averaged incremental ground-level SO_2 concentration at the points in space and time with the highest violation probabilities for the base case, the alternative and the alternative with a tall stack. This figure shows that the alternative with a tall stack peaks at a slightly smaller concentration value than the alternative with a shorter stack while exhibiting a tail similar to the base case. Integrating under these curves reveals that the alternative plant scenario results in ground-level concentrations less than the base case plant scenario 38% of the time while causing higher concentrations 7% of the time. A comparison of the tall stack alternative with the base case

EASTERN COAL SCENARIO 1975

Fig. 6.5. Probability vs. concentration for the eastern base case (solid line), eastern alternative (dotted line), and eastern alternative with a tall stack (dashed line) at the point in space and time where the second exceedance of $365 \mu\text{g}/\text{m}^3$ occurs.

shows that smaller ground-level concentrations occur 51% of the time and larger concentrations occur 2% of the time.

The relative air quality effects of using multiple facilities with tall stacks is shown in Table 6.2. The multisource air quality model was applied to the five sources (Fig. 4.11) operating with the alternative plant design and tall stacks. Exceedance and violation probabilities are calculated for 1975 based on an available increment of $30 \mu\text{g}/\text{m}^3$ for the same eleven receptors given in Table 4.3. Table 6.2 shows a comparison of these results to those given in Table 4.3. This table shows that the use of taller stacks is more effective in reducing violation probabilities for multiple sources than for a single source. In fact, for all eleven receptors considered, violation probabilities with tall stacks are considerably less than base case violation probabilities.

Table 6.2. Multi-source exceedance and violation probabilities

Receptor Number	One exceedance base case/alternative/tall stack	A violation base case/alternative/tall stack
6	2.44/5.90/5.24	6.80/9.88/2.63
7	0.04/2.16/0.56	6.73/7.57/3.11
12	6.38/8.09/1.43	6.87/11.51/3.24
13	1.96/4.82/0.56	6.87/10.46/2.65
14	0.39/2.65/0.81	7.25/11.06/3.32
20	0.01/1.97/0.38	6.73/7.09/2.21
21	0.56/6.25/4.02	6.73/5.43/1.82
30	0.13/3.02/2.02	4.09/7.96/2.22
32	0.16/1.19/0.39	7.00/10.83/2.37
63	0.24/3.53/1.09	4.44/9.97/1.94
93	0.03/2.84/0.05	5.41/5.78/0.69

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7. HEALTH EFFECTS

Regulatory schemes for emissions from a coal-fired power plant are based on the estimation of contribution of a given plant in a region to the total burden of pollutants in the region. The maximum acceptable levels of such pollutants, as set forth by ambient air quality standards formulated by the U.S. Environmental Protection Agency, are based primarily on the best available evidence concerning levels at which human health effects occur. For a detailed review of the evidence related to health effects of air pollution, and their use as a basis for regulatory action, see Walsh, et al. (1982).

Since this is the case, proposed changes in regulatory schemes for emissions from coal-fired power plants must consider the change in the total air pollutant burden, and the resulting impact on the health of the surrounding population.

The purpose of the procedures to be subsequently outlined will be to provide a description of the methods by which the health impacts of a particular proposed scheme for the regulation of coal-fired power plants are to be estimated.

The project itself assumes that a single coal-fired power plant is located in a metropolitan area. The plant is then assumed to operate under the current regulatory scheme (base case) and under the proposed alternative scheme. Output of the analytic portion of the project includes a simulation of the distribution of SO_2 emissions from a plant regulated under the alternative scheme, as well as the projected emissions of the same plant under the current regulatory scheme (Section 3). These projected emissions are then used to estimate probabilities of increased levels of sulfur dioxide (SO_2) in the area surrounding the site at which the plant is presumed to be located (Section 4) using information on current SO_2 levels at the locations (Figure 4.2). The distribution of the 24-hour average of SO_2 and the annual average level of SO_2 at various sites around the plant are estimated, and can be compared with the estimates produced using the current regulatory scheme.

This section will use these estimates as well as the population distribution of the chosen area to estimate the extent to which changes in regulatory policy will produce changes in population exposures above what are judged to be thresholds for short term effects and long term effects. The technique to be described would apply equally well to the simulation of effects resulting from regulatory changes for all the fossil-fuel burning plants in the area, provided the same output were available. Since air quality impacts for the western scenarios are significantly less than for the eastern scenarios (Section 4) health effects of the western scenarios are not analyzed.

There are certain assumptions which are implicit in the estimation of health effects of air pollution in general, as well as assumptions applicable to this particular project. These assumptions are discussed below.

Assumptions

Air pollution regulations are based on the control of the short term episode, regulated by the limit on the 24-hour average, and on the control of long term exposures, regulated by the limit on the annual average. The general assumption in the relationship of regulations to occurrence of health effects is that acute health effects are more closely related to very high level short-term exposures, while chronic effects are more closely related to the annual average.

Since both the regulations and the collected health effects evidence are based on the above dichotomy, the approach taken in estimating health impacts of regulatory changes will be based on (a) estimating changes in acute health effects resulting from changes in the distribution of the 24-hour average and (b) estimating changes in chronic effects resulting from changes in the annual average concentration of the pollutant.

Health effects resulting from air pollution are the result of a complex mixture of pollutants. Attempts to estimate the levels of effects observed in a population to levels of a particular component of the pollutant mixture are necessarily made under some assumptions concerning the level of other pollutants present in the air.

Nevertheless, U.S. air quality standards are based individually on the levels of the six criteria pollutants. Discussion of the impact of changes in operating characteristics of a pollutant-producing facility on ambient air quality are therefore most easily given in terms of changes in ambient levels of individual pollutants.

Since the burning of sulfur-containing fuels is the major single source of SO_2 in the air, SO_2 emissions are an important criterion in the regulation of a coal-fired power plant. Therefore, the work to date simulating the effects of regulatory changes has focused on change in SO_2 emissions. The health effects impacts of the regulatory changes must therefore also be based on changes in SO_2 levels.

The major air pollution episodes in this country and Europe which were associated with high levels of increased mortality all involved very high levels of the sulfur oxide/particulate complex. As a consequence of these disasters and their apparent association with high SO_2 levels, there was heavy emphasis on SO_2 in the setting of U.S. ambient air quality standards in the 1950's and 1960's. Subsequent work (Amdur, 1957; Amdur, 1959; Alarie, et al., 1972; McJilton, et al., 1973) suggests that oxidation products of sulfur dioxide, namely sulfuric acid and particular sulfates possibly acting synergistically with other pollutants, are the primary cause of the adverse health effects associated with SO_2 .

The use of SO_2 alone in estimating changes in health effects must therefore make the assumption that other pollutants are varying directly with SO_2 levels, and the SO_2 is serving as an acceptable surrogate for total pollution.

Review of Available Data

Effects at short-term acute exposure to high levels of the SO_2 /particulate complex include increased mortality at very high levels, as well as possible increased illness, particularly among those with preexisting respiratory disease.

The major air pollution episodes associated with increased mortality had observed 24-hour SO_2 levels at or above $1400 \mu\text{g}/\text{m}^3$ (Holland, et al., 1979). Studies of minor episodes in New York (occurring in 1953 and

1962) by Greenberg et al. (1962, 1963) showed that increases in deaths were evident when 24-hour average smoke levels were above 570-720 $\mu\text{g}/\text{m}^3$ with SO_2 concentrations between 850 and 1750 $\mu\text{g}/\text{m}^3$. Variations in risk of death at lower concentrations of TSP/ SO_2 below the extremely high levels found in these episodes are difficult to discern, because pollution episodes are often associated with extreme cold, which also accounts for increased mortality. According to MacFarlane (1976) short-term effects on mortality of pollution episodes below 1000 $\mu\text{g}/\text{m}^3$ of smoke and SO_2 are in no way outstanding compared with that occurring from sharp changes in temperature. Based on this and similar evidence, the World Health Organization in 1972 adopted the figure of 500 $\mu\text{g}/\text{m}^3$ for SO_2 and for particulates as the minimum associated with short-term changes in mortality.

Levels at which increased morbidity occur due to short-term high levels are also difficult to discern, again partly due to the association with low temperatures. The CHESS studies (EPA, 1974) indicate that adverse effects on elderly subjects having heart and lung disease and on asthmatics were experienced on days when the TSP concentrations were high and the 24-hour levels of SO_2 exceed the National Primary Standard of 365 $\mu\text{g}/\text{m}^3$. Again, it is believed that SO_2 itself is not the culprit, but that the associated high levels of suspended sulfate and possible other transformation products are causal factors.

Based on the available evidence, a threshold value of 500 $\mu\text{g}/\text{m}^3$ as a 24 hr average has been chosen for short term changes in mortality, with 365 $\mu\text{g}/\text{m}^3$ as the threshold for short-term changes in morbidity. Worst-case assumptions are made concerning the nature of effects on morbidity and mortality at these levels. For example, one might assume as a worst case a 5 to 10 percent change in mortality at levels at or slightly above 500 $\mu\text{g}/\text{m}^3$. Changes in morbidity cannot be so easily tagged to baseline levels, since estimates of morbidity for respiratory conditions depend heavily on the definition of the condition and on the population studied. As a worst case, one may assume that a certain percentage of the population (say 1 to 5%) experiences a worsening of

either respiratory or cardiovascular symptoms at levels above the primary 24 hour standard of $365 \mu\text{g}/\text{m}^3$.

Long-term effects of residence in high pollution areas have proved exceedingly difficult to quantify, partly because of the fact that the effects of pollution are almost certainly not as great as the effect of other factors which may differ between areas, such as cigarette smoking, industrial exposures and socioeconomic status.

The majority of studies of long-term effects of residents, in high pollution areas have been carried out in populations for which the annual average SO_2 level is well above the current primary standard of $80 \mu\text{g}/\text{m}^3$. However, one study of residents of the Salt Lake Basin found increased prevalence of chronic bronchitis at $90\text{--}95 \mu\text{g}/\text{m}^3$ of SO_2 and $60 \mu\text{g}/\text{m}^3$ of TSP (Knelson, 1978). A recent study of school children in Akron, Ohio, found increased attack rates of acute respiratory illness and evidence that respiratory airways were compromised at levels of $77.5 \mu\text{g}/\text{m}^3$ of SO_2 and $54.5 \mu\text{g}/\text{m}^3$ of NO_2 (Mostard, 1981). Particulate levels were not reported.

It is exceedingly difficult to quantify changes in health status due to changes in annual average values of SO_2 . However, it seems likely that very small changes in the annual average will not produce discernible health effects. Results of the simulation (Section 4) indicate that the regulatory changes being studied produce very small reductions in the annual average SO_2 levels, when applied to only one facility. Such regulatory changes applied to a number of facilities may produce larger expected reductions in the annual average SO_2 levels, which will need to be considered in an analysis of overall health impacts.

Comparison of Health Effects

The estimated number of acute effects is given by

$$y = P \cdot N_i \cdot R_i$$

where P is the probability of exceeding a given threshold level ($365 \mu\text{g}/\text{m}^3$ or $500 \mu\text{g}/\text{m}^3$ as discussed above), N_i is the number of people exposed in each probability range, and R_i is the risk of mortality if $500 \mu\text{g}/\text{m}^3$ is exceeded or the risk of morbidity if $365 \mu\text{g}/\text{m}^3$ is exceeded.

The method for determining the probability values for the base and alternative cases is described in Section 4. As an extreme worst case, we assume that the increase in mortality will be about 10% if exposure exceeds $500 \mu\text{g}/\text{m}^3$. The annual mortality rate for the U.S. population is about 9/1000. Thus the risk of mortality, R_i would have an upper bound of about 9×10^{-4} mortality/year ($\sim 10^{-3}$) if exposure exceeds $500 \mu\text{g}/\text{m}^3$.

Estimated annual mortalities for the base and alternative cases are given in Table 7.1. The expected annual mortalities in the alternative case are three times those of the base case. However, the absolute estimates are low. The expected total excess mortalities of the alternative case over the base case would be only about 0.1 deaths/yr in a total population of 1.6 million, even under the worst case assumption of a 10% increase in mortality above $500 \mu\text{g}/\text{m}^3$ exposure. The total increase in risk for an individual would be less than 1×10^{-7} as compared to an annual mortality rate of 10^{-3} . Thus the increase in risk associated with the alternative case is essentially negligible.

Table 7.1. Estimated annual mortalities for the base and alternative cases

Probability of exceeding $500 \mu\text{g}/\text{m}^3$	Population exposed		Expected annual mortalities	
	Base Case	Alternative Case	Base Case	Alternative Case
$0-3.3 \times 10^{-5}$	1.65×10^6	1.34×10^6	5.4×10^{-2}	4.4×10^{-2}
$(3.3-6.7) \times 10^{-5}$	0	10^5	0	6.7×10^{-3}
$(0.67-1.0) \times 10^{-4}$	0	4.2×10^4	0	4.2×10^{-3}
$(1.0-5.0) \times 10^{-4}$	0	1.5×10^5	0	7.5×10^{-2}
$(0.5-1) \times 10^{-3}$	0	7×10^3	0	1.7×10^{-2}
	1.65×10^6	1.65×10^6	5.4×10^{-2}	1.6×10^{-1}

As a worst case for morbidity, we assume that 5% of the exposed population will be affected if exposure exceeds $365 \mu\text{g}/\text{m}^3$. The estimated number of people effected is given in Table 7.2. There are about four times as many people affected in the alternative case as in the base case. However, the probability that an individual out of the population of 1.6 million will be affected is less than 10^{-3} . The plant under study actually contributes only about 10% to the total exposure under worst case conditions (the ambient level from other sources is about $335 \mu\text{g}/\text{m}^3$). For areas where the existing ambient levels were low, the probability of exposure exceeding $365 \mu\text{g}/\text{m}^3$ due to the operation of one plant would be much lower. Potential problems arise, as expected, when one or more plants are to be located in an already polluted area. In such cases, the problem needs to be studied in more depth with more realistic risk multipliers.

Table 7.2. Number of persons experiencing excess morbidity for the base and alternative cases

Probability of exceeding $365 \mu\text{g}/\text{m}^3$	Population exposed		Morbidity cases	
	Base	Alternative	Base	Alternative
0-0.1	1.5×10^6	1.1×10^5	75	6
0.1-1.0	1.1×10^5	1.1×10^6	55	550
1.0-2.5	1.1×10^4	2.4×10^5	14	300
2.5-5.0	1.0×10^3	1.4×10^5	3	350
5.0-7.5	6.0×10^3	6.6×10^4	225	248
7.5-10.0	0	8.9×10^3	0	44
10.0-12.5	0	5.9×10^3	0	62
12.5-15.0	0	3.9×10^3	0	30
	1.6×10^6	1.6×10^6	372	1590

The annual average exposure in the alternative case will be approximately 10% less than in the base case. However, the change in total exposure will be less than 1%, because the plants are contributing less than 10% to the total SO₂ burden. There is little evidence that exposures at or below the allowable annual averages produce any effects. In spite of this, some have estimated effects based upon linear, nonthreshold exposure-response relationships. As an example only we will apply such a relationship. If we assume that roughly 1% of the population exposed ($10^{-2} \times 1.6 \times 10^6 = 1.6 \times 10^4$) are affected at levels of about 50 µg/m³, then the reduction in effects under the alternative case would be 160 cases of perhaps slightly increased morbidity. Multiple plants in a given area would have a greater impact but the situation would need to be studied in greater depth to draw conclusions any more quantitative than the very rough estimates given herein.

Acute effects (mortality and morbidity) depend critically upon threshold levels of exposure. Thus they depend critically upon ambient pollutant levels. Estimated effects will thus vary greatly from location to location. In an area where ambient levels are already high, the addition of one plant can be important while in areas where ambient levels are low, several plants could be added without exceeding critical thresholds.

Potential cumulative effects due to chronic exposures (annual average) should be lower in the alternative case. The contribution of acute exposures to chronic effects somewhat confounds the picture. But given current thinking in the regulatory sense, one can assume a reduction in chronic effects if annual average exposures are reduced. One assumes that a reduction in SO₂ will be accompanied by a reduction in other pollutants, but again the degree of reduction depends on the relative magnitudes of other sources.

An interesting possibility that could remedy the small increases in acute effects is the use of tall stacks. The use of tall stacks was discontinued because of regional and national pollution problems such as sulfates and acid rain. Since in the alternative case discussed herein, the annual average exposures are lower, tall stacks might be used to avoid acute effects. The number of persons experiencing excess morbidity if a

tall stack were added for the alternative case is given in Table 7.3. Comparing Tables 7.2 and 7.3, the alternative case with tall stack would reduce the number of effects to about two times the base case number.

Table 7.3. Number of persons experiencing excess morbidity for the alternative case with a tall stack

Probability of Exceeding 365 $\mu\text{g}/\text{m}^3$ -%	Population Exposed Alternative Tall Stack Case	Morbidity Cases
0.0-0.1	6.8×10^5	6
0.1-1.0	7.4×10^5	300
1.0-2.5	2.0×10^5	250
2.5-5.0	2.3×10^4	57
5.0-7.5	3.0×10^3	11
7.5-10.0	0	0
10.0-12.5	0	0
12.5-15.0	0	0
	<hr/> 1.6×10^6	<hr/> 652

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8. CONCLUSIONS AND RECOMMENDATIONS

The stochastic approach of air quality impact assessment used in this study provides some interesting insight into the true costs and benefits associated with SO₂ controls. The total life cycle costs of operating a facility are similar, but the alternative controls allow the site-specific costs, such as lime, labor, fuel and solid waste disposal, to be minimized by the plant operator. In addition, the true emission limits are set by the regulatory authority, based upon measurable (mean and variance of coal sulfur) quantities, not subjective reductions issued as a form of self-protection by the plant owner. Local coals may become viable options at facilities; a savings of \$1.00 per ton delivered costs would result in \$50 million in savings over the life of the facility investigated in this study.

Changes in air quality regulations will result in intangible benefits to facility operators as well. By allowing additional operating hours during upset conditions, plant shutdowns may be postponed for some hours, resulting in longer, and potentially less damaging, plant shutdown cycles. These longer shutdown cycles may also allow the grid manager to keep a facility generating for an additional few hours, thus stabilizing the entire grid and reducing the demand placed on expensive replacement power.

The air quality impacts of this modified approach, as applied to the cases considered in this study, are negligible. The control alternatives would allow the emission of less SO₂ over the course of one year than do present practices at a comparable cost, resulting in less sulfur available for long range transport, and potentially reducing the total atmospheric sulfur loading. By specifying the emission characteristics required of a facility, the regulatory agency can both specify the allowable violation probability for short term standards and reduce the total sulfur emitted by any given facility.

In conjunction with the air quality impacts of the proposed approach, the effects on human health can be limited. By specifying a maximum violation probability of the short-term SO₂ standards, the fuel characteristics of each alternative are determined. For a single isolated

source, relative changes in acute effects exist; however, absolute differences in acute effects are negligible and likely undetectable. The multiple source analysis shows that both relative and absolute changes in acute effects are negligible. These negligible acute effects may in fact be more than offset by reductions in annual emissions, and the resulting reductions in chronic SO_2 levels.

The effectiveness, cost, and health effects associated with varying levels of SO_2 controls are discussed in the previous sections of this document. The realization of the alternative controls investigated in this study do depend upon a shift in regulatory emphasis being made, but such a shift could well offer significant benefits to industries presently controlled by air quality laws. By recognizing the emissions variability inherent in available fuels, air quality regulations will become more realistic, will continue to protect and improve the environment, will allow greater flexibility by the regulated industries, and will result in savings to the plant operators. The multiple source air quality analysis shows that as the number of facilities sited within a given region, and as the allowable increment is approached, the stochastic regulations allow plant designs which could reduce violation probabilities below those which are predicted for facilities operating under existing regulations. This implies that the stochastic approach offers plant operators cost-effective options which allow an increased number of facilities to be located in a given region before the full allowable increment is consumed.

The stochastic approach could lead to regulatory procedures which would allow power plants a fixed finite probability of violating air quality standards. This would offer plant operators greater flexibility by allowing a range of sulfur dioxide mean emission rates and emission rate standard deviations. This compliance range could be established on a site specific basis according to the locally most restrictive air quality standard (i.e., 24-hr NAAQS, 24-hr PSD, 3-hr NAAQS, 3-hr PSD). Figure 8.1 shows such a compliance map for cases considered in this study based on the 24-hr NAAQS for sulfur dioxide. Compliance for both a 5% and 10% violation probability are shown. As can be seen in this figure, such an approach would allow both an increased mean and an increased standard

COMPLIANCE MAP

Fig. 8.1. Compliance map base on an allowable 10% violation probability (solid line) or an allowable 5% violation probability (dashed line) with respect to the 24-hr NAAQS for sulfur dioxide.

deviation as compared to current regulations. This would likely lead to unacceptable air quality impacts and health effects. Such situations can be eliminated by imposing an upper bound on the mean emission rate. This bound would be based on either the annual average sulfur dioxide standard or the applicable NSPS emission limit, depending upon which is the more restrictive. Figure 8.2 shows such a compliance map for the cases considered in this study. Here the most conservative upper bound for the mean emission rate is the NSPS requirement of an 85% mean sulfur removal. The results of this study suggest that regulatory enforcement based on such a compliance map will not result in air quality or health changes but would provide a consistent enforcement protocol based on a consolidation of regulations while allowing utilities greater flexibility in both plant design and plant operating procedures.

COMPLIANCE MAP - EASTERN COAL SCENARIOS

ORNL-DWG 82-13928

Fig. 8.2. Compliance map for the eastern scenarios based on an allowable 5% probability of violation of the 24-hr NAAQS for sulfur dioxide with an upper bound on the mean emission rate based on the NSPS emission limitation.

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