REGIONAL AIR POLLUTION ANALYSIS*

M. L. Frankel**
Federal Water Quality Administration
Washington, D. C.

D. H. Lewis
TRW Systems Group
Washington, D. C.

Summary

Metropolitan regions have been experiencing a combination of population growth and industrial expansion which has led to an increase in the degree and complexity of air pollution problems. Effective solutions to these problems require analysis of such factors as pollution sources, transport of pollutants in the atmosphere, prevention and control methodologies, and regional economic impact. On the basis of the results obtained from such an analysis, local control legislation can be developed which will fulfill the specific air quality requirements of a given region.

Analysis of regional air pollution problems and their solutions is effectively performed through the application of computer modeling techniques. Mathematical models may be used to represent the actual environment and estimate the feasibility and impact of proposed solutions. Such an analytical system provides a rapid and accurate means of determining the types of pollutant emission regulations which will be required throughout the region.

The Regional Air Pollution Analysis program includes mathematical models representing the atmospheric diffusion of pollutants, the cost and effectiveness of pollution control measures, the impact of pollution control expenditures, and potential strategies upon which control legislation may be based. The program thus provides an objective means for analyzing both the extent of the region's air pollution problems and the adequacy of potential solutions. Sample results are provided for several steps in the process of preparing an air quality implementation plan. These results represent implementation planning studies in Cincinnati, Washington, D.C., Philadelphia, and St. Louis.

Introduction

The Regional Air Pollution Analysis computer program, being developed by TRW Systems for the National Air Pollution Control Administration represents a means by which state and local agencies empowered to control air pollution may define the causes, recipients, and methods for control of pollution within their jurisdictions. To account for both Federal and local government authority, specific distinction is made in this program between stationary and mobile air pollution sources. Since mobile sources are relatively uniform in their emission characteristics, are readily controlled at points of manufacture, and are widely distributed throughout the nation and its economy, Federal control of such sources is more efficient than local control. Stationary sources, on the other hand, are strongly influenced by the physical characteristics of the particular region, as well as by the local economy and industrial patterns, and are thus more susceptible to analysis and control at the local level.

The technical aspects of air pollution are reasonably well understood. The major pollutant sources are known, as are the techniques for pollution control. We are faced with more than a problem of control technology, however. The human factor is highly significant, since man is both the polluter and the primary recipient of pollutants. We lack a thorough understanding of the social, economic, and political aspects of the air pollution problem, and are thus unable at present to develop the high degree of motivation and incentive required to achieve our air quality goals.

A chief obstacle to clean air is of course man the polluter. Many of us have viewed the atmosphere as a limitless and therefore free resource. Major polluters have resisted moves in the direction of air pollution control, since the extensive costs involved in such control would, they felt, be prohibitive.

Overloading of the atmosphere has made the air pollution problem more apparent to man the polluted, however, and a growing segment of our society is becoming concerned over the declining quality of the air we breathe. An increasingly vocal group of citizens have come to view the atmosphere not as unlimited but as a scarce and valuable resource. The rapidity with which we are depleting this resource is staggering, and it now appears probable that we will "run out of air" not at some vague, far-off future time but, within the comprehensible future. Our society is beginning to realize that it is this generation and its children, rather than future generations, that will fall victim to misuse of a most important national asset.

To reconcile the opposing views of the air pollution problem, we must first gain a firmer understanding of both the costs of air pollution control and the gains inherent in better air quality. These factors must be considered in relation to alternative air pollution control strategies.

Reasonable qualitative estimates of air pollution control costs and the effect of these expenditures on air quality are available. In general, this cost relationship is non-linear (Figure 1), with the rate of air quality improvement diminishing as investment in air pollution control increases. The relationship between air pollution damage expenses and air quality levels is less well understood and may be linear or also non-linear, with the rate of decrease in pollution damage remaining constant or diminishing for each additional increase in air quality levels.

Both of these cost relationships must be analyzed simultaneously to determine society's total expenses in air pollution control and air pollution damage. The results of this analysis will indicate the atmospheric management strategy which balances the rate of air pollution control expenditures with the rate of air quality benefits.

Constructive steps have already been taken toward such a combined analysis. Control techniques[1,2]

*The work upon which this publication is based was performed pursuant to Contract No. PH 22-68-60 with the U.S. Public Health Service, Department of Health, Education and Welfare.

**On leave from TRW Systems Group, Washington, D.C.

and air quality criteria[3,4] documents were issued under the Clean Air Act as amended, and computer simulation tools have been developed for use in carrying out the guidelines of this Act through analysis of the regional air pollution environment.

Federal Legislation

The design of operational computer programs for application in pollution control at the regional level has been based on the requirements indicated in the Clean Air Act as amended. This Act provides for the establishment of an intergovernmental system for the prevention and control of air pollution on a regional basis. To put this system into operation, the Department of Health, Education and Welfare must designate Air Quality Control Regions and issue air quality criteria and reports on control techniques. State governments are then expected to establish air quality standards for the regions and to adopt plans for implementation of these standards. The air quality standards and implementation plans prepared by the states must be submitted to HEW for review.

Air Quality Control Regions represent the local, operational level for air pollution control as envisioned in the Act. The borders of a given region will be established so as to include the principal emitters or sources of pollutants for the area, together with a majority of the receptors (people, plants, animals, and materials) exposed to these pollutants. Generally, the major metropolitan areas represent the highest concentrations of both emitters and receptors, although the pattern of receptors affected by pollution will vary according to local meteorological conditions.

The Department of Health, Education and Welfare is responsible for developing and issuing air quality criteria. These criteria are to be based on current analyses of the adverse effects of specific air pollutants and combinations of pollutants on man and his environment. Although the evidence in the criteria documents will not necessarily be based precisely on levels of exposure below which there are no adverse effects, they will nonetheless provide quantitative guidance to the States for establishment of regional air quality standards. The documents covering criteria for sulfur oxides and suspended particulate matter indicate effect levels shown in Table 1.

For each of the pollutants covered by a criteria document, the Department of Health, Education and Welfare issues a report on control techniques. These reports provide engineering-handbook information on the physical characteristics, operating characteristics, and cost characteristics of control measures. From these documents, control cost-effectiveness information can be obtained for control devices, such as precipitators and fabric filters, and for non-device control measures, such as the use of low-sulfur-content fuels or alterations to basic industrial processes which lessen pollutant emissions.

On the basis of air quality criteria, control technology, and regional boundaries, the States establish air quality standards for the protection of public health and welfare. These standards provide the basis for controlling existing sources of pollution and for preventing future regional growth from adding to the pollution problem. These goals are stated in the form of desired limits on the level of each particular air pollutant. The goals may reflect more than one air quality standard, specifying several minimum and higher air quality levels. The goals must also preclude the possibility of significant deterioration in existing air quality levels.

Implementation plans are blueprints for establishing and maintaining these air quality standards. The heart of an implementation plan is its emission control strategy, which sets forth requirements for the prevention, abatement, and control of a given type of air pollutant and establishes a timetable for obtaining compliance with these requirements. Legally enforceable emission standards applicable to stationary sources of the pollutant will ordinarily be a principal element of the emission control strategy. The strategy may also include regulations pertaining to such factors as fuel use, location of new industrial plants and other potential pollutant sources, open burning, and disposal of solid waste materials.

Regional Air Pollution Analysis Program

To assist the Federal Government and Air Quality Control Regions in developing and evaluating meaningful air pollution control strategies, the Regional Air Pollution Analysis (RAPA) Program* has been developed. The regional air quality implementation process is based on the application of a set of stationary source emission controls in the form of emission standards. The many combinations of these standards result in a variety of alternative control strategies. Through application of computer simulation techniques, the Program is used in selecting appropriate emission standards, evaluating the resulting air quality, and estimating the costs associated with the various alternative control strategies.

The need for diffusion modeling in the preparation of the implementation plans required to meet Federal legislation has been pointed out by Middleton.[5] The use of a systems analysis approach to implementation planning, combining a diffusion model and cost-effectiveness models, has been suggested by a number of authors. The history of the systems analysis approach and some particular advantages to be gained by applying it to the air pollution control problem are discussed in a paper by Wilson and Braunheim.[6] Perhaps the first demonstration of a complete systems analysis model is the work of the Program Analysis Group of the National Air Pollution Control Administration reported in Reference 7. Although only a pilot scale model was developed and applied to a hypothetical city, many of the ideas presented here have been used in later work. An application of the systems analysis technique to a full scale region is presented in the work of Burton and Sanjour.[8] The Kansas City region was selected, and a number of control strategies were evaluated, including least cost, maximum control (best device on every source), and a regionwide restriction on fuel sulfur content. A limitation of this study is the requirement for manual selection of control alternatives, and the fact that any selected strategy will not be in the form required for implementation planning, i.e., there is no distinction between political jurisdictions nor for differences in emission standards for different source categories, etc.

The RAPA program described in this paper is similar in structure to the two models referenced above[7,8], but is designed to provide a more realistic simulation of the practical problems encountered in developing control strategies, since the program structure allows considerable source-to-source control variation but retains the advantages of a computerized system. In addition, the distinction between political jurisdiction allows the emission standards selected to be written directly into law.

*The Implementation Planning Program, a limited version of RAPA, was developed for use by local air quality control region officials.

The core of any air pollution planning program is the diffusion model which computes pollutant ground-level concentrations given source emission rates and a description of the local meteorology. The nature of air pollution problems and, consequently, the appropriate diffusion model selection, varies according to the time and space scale adopted. The scale of the problem addressed by the RAPA program is regional (major city plus environs) rather than local (street corner), or global, and we are concerned with chronic (long term), as well as short term (hours) exposures. Most urban diffusion models, including the one used in RAPA, are based on some form of the Gaussian plume rise equation. A review and comparison of these models has been prepared by Wanta.[9]

A model which is capable of handling time scales on the order of one hour to over one year has been developed by Hilst.[10] This model requires a tremendous amount of detail in the wind field description, more than can be provided for most regions where the only meteorological data available is taken at a single airport Weather Bureau station.

The RAPA diffusion model is based on combining the work of Martin and Tikvart[11] (long-term-average pollutant concentrations predicted using data from a single meteorological station) and that of Larsen[12] (short term concentrations). The current RAPA program structure has evolved as experience was gained in the simulation of control strategies for several air quality control regions. FØRTRAN IV is used throughout the models; the data system is written in CØBØL.

The selection and evaluation of emission standards in a control strategy is restricted to the political jurisdictions within an air quality control region. Pollutants from man-made sources outside this region and natural ground-level background concentration are assumed to be uniformly distributed and unaffected by meteorological conditions or emission standards. When a sufficient number of regions use this type of computer simulation technique, it will be possible to analyze the effects of control strategies in one region on the air quality in a neighboring region.

Finally, the accuracy with which the computer simulation models predict air quality conditions and control costs is dependent on the quality of input information. As in most computer simulations of the real world, better input information results in better output results.

Program Inputs

A wide variety of input information is required by the Program, including meteorological data, air quality data, a source emission inventory, data on air pollution control technology, regional economic data, and descriptions of the emission standards to be used in candidate control strategies.

The meteorological data required by the Program describe those meteorological elements which have an important effect on the atmospheric transport and dispersion of air pollutants, including wind direction, wind speed, stability class, mixing depth, ambient temperature, and ambient pressure. Wind direction determines whether or not the pollutant is transported from a pollutant emission source to a particular receptor location, and wind speed determines the amount of air available for dilution of the pollutant. Atmospheric stability, a measure of turbulence, may be in the form of an arbitrary measurement based on time of year, amount of solar radiation, and wind speed, or it may be a conversion from data on vertical temperature differences. Mixing depth determines the amount of vertical mixing possible in the atmosphere. Normally, air pollutants can only mix through a relatively shallow atmospheric layer. The mixing depth may be as high as 5 or 6 thousand feet in the afternoon and only a few hundred feet at night. Data inputs for these four most important meteorological elements are available from the National Weather Records Center (NWRC), operated by the Environmental Sciences Services Administration in Asheville, North Carolina. Here all meteorological data collected by Federal agencies are stored, tabulated, and summarized for the user's convenience.

To be compatible with the requirements of the implementation plan, an air quality monitoring network must provide data for comparison with air quality standards, analysis of emission control effects, evaluation of short-term emergency conditions, and verification of the atmospheric diffusion modeling. Specifically, data are required on sampling station location,annual arithmetic mean concentration, and standard geometric deviation. The amount and quality of such data needed for the verification process cannot be stated in an absolute sense. Naturally, as more data becomes available and as the quality of the data improves, more confidence can be applied to the atmospheric diffusion modeling.

An emission inventory is used to identify the existence of air pollution sources and to define the location, type, magnitude, frequency, duration, and relative contribution of the emissions from these sources.

The ideal stationary source emission inventory would include emission estimates for every source in an air quality control region, as determined from stack gas sampling. Since this is not possible for all sources and pollutants, various techniques have been developed to estimate emissions from sources where the above data are not available.

Several types of air pollution sources are encountered in any given metropolitan area. Generally, these sources can be divided into four major categories and several subcategories. The breakdown used by the National Air Pollution Control Administration in presenting emission inventory data for the computer program is as follows:

FUEL COMBUSTION (Stationary Sources)

- Residential
- Commercial-Institutional-Governmental
- Industrial
- Steam-Electric Power Plants

INDUSTRIAL PROCESS LOSSES

SOLID WASTE DISPOSAL

- Incineration
- Open Burning

TRANSPORTATION (Mobile Sources)

- Motor Vehicles
- Aircraft
- Railroads
- Ships

Information on these categories of pollution sources is further broken down according to two types: (1) Area Sources and (2) Point Sources. Area sources include small residential, commercial, governmental, institutional, and industrial fuel combustion operations, on-site solid waste disposal, and mobile sources. Point sources include major fuel users, incinerators, open burning dumps, and industrial process sources.

The costs and efficiencies associated with air pollution control devices influence the engineering and economic consequences of control strategies. Inputs to the Program must account for 1) regional information such as labor costs, sales tax, interest rates; 2) pollutant source information from the emission inventory; and 3) control device information such as installation costs, manufacturers' price, expected life, rated efficiency, etc. The Program contains a great deal of this information for the devices described in the control techniques documents [1,2] published by the Department of Health, Education and Welfare. In addition, the program allows the user to supplement this information with new control devices or more refined data on devices already included in the Program.

Legal regulations prohibiting or restricting emissions into the atmosphere have long been a major tool used by communities against air pollution. Many of the earlier control regulations were designed to effect a reduction in local nuisance problems. More recently, control regulations have been adopted with a view toward achieving a general improvement in the quality of a community's air resources.

Emission standards, from which emission regulations are developed, generally limit the amount of a pollutant which may be emitted into the atmosphere from a source. Figure 2 illustrates a typical emission standard format limiting allowable emissions to some function of plant capacity such as the quantity of input raw materials. The allowable emission may be either directly stated (e.g., a process/weight-type standard) or implied(e.g., a specific type of fossil fuel). It is usually necessary to adopt several standards in order to control all the pollution sources in the area. For example, particulate pollution control may require separate emission standards covering industrial processes, fuel combustion, and solid waste disposal.

The specific emission standards to be used as candidates for a region's control strategy must be determined on the basis of many factors, including such aspects as types of industry and local availability of different qualities of fuel for combustion sources. The Program has been designed to accept an infinite variety of emission standards, the only requirement being that the standards can be described in mathematical terms.

Based on direct control costs, borne by the industries affected by a control strategy, the Program estimates the total economic impact on the region. This impact is measured in terms of gross regional product, industrial output, changes in profit, etc. The input information required for this type of economic analysis includes industrial data on employment, value-added, exports and imports, regional data on local taxes, government expenditures, regional income, labor force, and many other economic factors. Both time series and cross sectional data have been used in the estimations.

Program Structure

The Program is divided into several separate elements: an Atmospheric Diffusion Model, Control Cost Model, Control Strategy Model, Regional Economy Model and an Information System which stores and maintains air pollution control data and provides this data to each of the models. Figure 3 illustrates the major models in the Program and their interaction with human decision which permit the user to determine the amount of control based on the atmospheric diffusion, air quality standards, available control technology, and the cost of air pollution control.

The purpose of the several models which constitute the Program is to provide an integrated and comprehensive analytical tool to assess the air pollution problem in an air quality control region and to assist local officials in the development of control strategies designed to meet the regional air quality goals.

Atmospheric Diffusion Model

The first step in examining the existing or projected regional air quality conditions is an analysis of the movement of pollutants. The atmospheric transport of pollutants from any given source takes place through convection(due to the net air motion) and diffusion(due to random atmospheric turbulence). The pollutant plume moves away from the source in the downwind direction and expands laterally. The Atmospheric Diffusion Model provides mathematical transfer functions between individual source emissions within the region and regional measures of air quality. In addition, the transfer functions are also used to estimate the effects of various source emission standards contained in overall control strategies on regional air pollution.

Since the objective of the Atmospheric Diffusion Model is both to produce a frequency distribution of pollutant concentrations and to determine the individual influence of each source at each receptor point, a combination of two modeling techniques is used. A deterministic technique transforms source emission data into average ground-level long-term pollutant concentrations, and a statistical technique estimates a corresponding frequency distribution for ground-level concentrations at different averaging times. It should be noted that the deterministic model alone cannot be used to develop a concentration frequency distribution, since the upper end of the distribution (i.e., those concentrations exceeded, say, one percent of the time, or the expected annual maximum) occurs under short-term meteorological conditions.

The deterministic model[11] computes the arithmetic annual average ground-level concentration resulting from specified area and point source emissions on the basis of the Pasquill-Gifford point source formulation. Area sources are aggregations of small sources (e.g., a residential area) while point sources are major emitters of effluent gas, usually from a plant stack. The coordinate system for point sources has its origin at ground level at the base of the stack (i.e., directly below the effective point of emission). The X-axis extends horizontally in the mean wind direction, the Y-axis is horizontal in the cross-wind (and cross-plume) direction, and the Z-axis is vertical. Area sources are handled in terms of an equivalent point source. The "effective stack height" (or effective height of emission release) is the height at which the plume center line becomes horizontal. The effective stack height is the sum of the physical stack height and an incremental factor related to the buoyancy and vertical momentum of the effluent.

Ground-level concentration estimates are obtained by setting z = 0 in the general Pasquill-Gifford formulation,

$$\chi(x,y,z;\ h) = \frac{10^6 Q}{\sigma_y \pi \sigma_z u} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \quad (1)$$

where:

$\chi(x,y,z;\ h)$ = pollutant concentration at point x,y,z for an effective stack height h, micrograms/meter^3

Q = emission rate, grams/sec.

u = mean wind speed, meters/sec.

σ_y, σ_z = standard deviation of the plume concentration distribution in the cross-plume and vertical directions, meters. (σ_y and σ_z are given as functions of downwind distance and atmospheric stability.)

For a source which emits at a constant rate from hour to hour and day to day, Equation (1) can be modified to yield estimates of annual average concentrations if applicable stability wind rose data are available. A wind rose tabulates the frequency of occurrence for each wind direction and wind speed class during a standard climatological period.

A stability wind rose contains the same information, but it is further divided according to atmospheric stability classes.

Although the change in wind direction is a continuous function over the long-term period, for computation purposes discrete wind directions are specified with respect to a 16-point compass, corresponding to 22.5-degree circular sectors. The concentration at a given receptor location is composed of proportional contributions from both the sector containing the receptor and from the nearest adjacent sector. The linear interpolation term is given by (c-y)/c, where y is the crosswind distance between the receptor and the sector center line, and c is the sector width at the receptor location.

Use of the linear crosswind distribution changes the form of Equation (1) to the univariate Gaussian distribution:

$$\chi = \frac{2 \times 10^6 Q(c-y) / c}{u\sigma_z \sqrt{2\pi} \; (2\pi x/16)} \exp\left[-\frac{1}{2}\left(\frac{h}{\sigma_z}\right)^2\right] \qquad (2)$$

Vertical plume rise is inhibited by the existence of a stable atmospheric layer having a base lower than the effective stack height (the layer elevation will generally range between 100 and 3,000 feet). The rate of vertical mixing is greatly reduced in such a layer, and the base of the layer can thus be considered as an effective "lid" on vertical transport of pollutants. The RAPA model includes provision for modeling this inversion layer phenomenon.

For a specific source-receptor configuration, an estimate of χ is obtained by choosing a representative wind speed for each wind speed class and solving the appropriate equation for all wind speed and stability classes appropriate for the time period in the geographical area of interest. The average concentration, $\overline{\chi}$, is obtained by summing all concentrations and weighting each one according to its frequency for the particular wind direction, wind speed class, and stability class. The average concentration is:

$$\overline{\chi} = \sum_{\Theta} \sum_{N} \sum_{S} F(\Theta,N,S) \; \chi\,(\Theta,N,S) \qquad (3)$$

where:

$F(\Theta,N,S)$ = normalized frequency during the period of interest for wind direction interval Θ, wind speed class N, and stability class S.

$\overline{\chi}(\Theta,N,S)$ = average ground-level concentration calculated from Equation (2).

The total concentration at a specific receptor is obtained by summing the results of Equation (3) over all point and area sources. For each of the 16 wind direction intervals, wind speed is defined in 6 categories and stability class in 5 categories. Thus, a three-dimensional array of 480 categories is established. (However, only a few wind directions result in non-zero contributions for specific source-receptor pairs. Thus, the computation time is reduced significantly.) Vertical variations in wind speed and wind direction are not accounted for in the present model.

An added feature to the operation of the deterministic model is the use of a "correlation" option, a method of adjusting and verifying the model to make the computed ground-level concentration consistent with available measured ground-level concentrations. The method of adjustment uses least-square regression lines based on plots of measured concentrations vs. theoretical concentrations for each pollutant.

The statistical model[12] uses correlated arithmetic averages from the deterministic model and input values reflecting the geometric standard deviation for each pollutant to estimate desired frequency distributions (i.e., maximum values and frequencies of occurrence with which specified values are exceeded). The key assumptions involved in the use of the statistical segment are that (1) ground-level air pollutant concentrations are approximately lognormally distributed for all pollutants and for all averaging times, and (2) the geometric standard deviations are known for each pollutant and are independent of the concentration magnitude but dependent upon its location within the region. Given the computed arithmetic averages and the input geometric standard deviations, the maximum, minimum and geometric mean concentrations may be computed for any averaging time. These quantities are all straight lines on a log-log plot, as shown in Figure 4.

Control Cost Model

The purpose of computing control cost and control effectiveness values is to provide an indication of the lowest-cost set of air pollution control measures which will satisfy required control regulations. The direct costs of these control measures, when summed over their application to all air pollution sources, provide estimates of regional air pollution control costs. By calculating the direct costs of air pollution control and the efficiencies of the selected control measures, this model provides the Program with estimates of point source control cost-effectiveness measures for evaluating candidate air pollution control strategies.

Each air pollution source (e.g., an industrial plant, power generating station, or apartment house) has one or more control-measure options for reducing its pollutant emissions. Each control measure has various cost and control efficiencies, depending on the source to which it is applied. The Control Cost Model sorts out applicable source/control measure combinations and provides the user with cost-effectiveness estimates for each specific point source or source category.

Figure 5 illustrates the cost of control applied to the chemical industry (Standard Industrial Classification 28) in the St. Louis and Cincinnati regions. Total annual costs are shown, including manufacturer's price (based on the Control Techniques document[3,4]) installation costs, annual capital charge, and operation and maintenance costs. In computing these major expense items, the model takes into account such factors as equipment depreciation schedules, interest rates on capital, and cost or credit for pollutant disposal. The model also considers variations in costs from region to region to account for equipment transportation costs, service utility connections, labor costs, etc.

The outputs of the Control Cost Model may be varied according to several user options. Results can be grouped to display the set of alternative control measures available to any single air pollution emission source, together with estimates of the annual cost and efficiency of each control measure. By further aggregation of the results, a similar display can be constructed for groups of sources (e.g., Standard Industrial Classification codes) or for all combustion sources. Figure 6 illustrates the costs of maximum control technology to a group of major industry categories in the St. Louis Air Quality Control Region. In this case, maximum control represents the most effective device or non-device control measure available to each plant.

Control Strategy Model

A control strategy is essentially a plan for reducing pollutant emissions from specific sources within a specified period of time. The emission limitations of a control strategy generally include emission standards applicable to air pollution sources, regulations pertaining to fuel use, rules for the location of new industrial plants and other sources of air pollution, restrictions on open burning, plans for disposal of solid wastes, etc.

Control strategies are preventive or controlling schemes directed at particular pollution source categories (e.g., combustion sources, industrial sources, Federal facilities) through emission regulations such as pollutant emissions rates versus input process weight. The Program can process a control strategy whereby maximum control technology is applied to fuel combustion sources, process weight restrictions are applied to industrial sources, and potential emission standards are applied to solid waste disposal sources.

The purpose of the Control Strategy Model is to provide a reasonably accurate and quantitative procedure for testing the impact of alternative control strategies in a computer-processed mathematical model and assessing the degree to which air quality goals are met under each strategy. The Program can thus be used as a "gaming" tool, with the user specifying a control strategy, observing the resulting change in regional air quality, and, on the basis of the results, modifying the specifications for another "run."

In the context of the Program, a control strategy is considered to be an overall plan which specifies the types of air pollution sources to be controlled and methods for their control. The objective of a strategy is to reduce both long- and short-term air pollution. As long-term air quality standards are made more and more stringent, the frequency of short-term emergency conditions will be correspondingly reduced. The Control Strategy Model, in conjunction with the statistical segment of the Atmospheric Diffusion Model, allows the user to observe the interaction between chronic and acute regional air pollution problems.

The Program postulates the type of control measures which would be used by an air pollution source facility to meet the proposed source emission requirements. Inherent in the Program is the assumption that individuals or corporations responsible for the air pollution sources will use control techniques which result in the lowest cost to the source facility. Simulation of a strategy with assumed lowest-cost control measures applied to the sources of pollution assists the user in evaluating implementation plans with regard to reasonable ground-level pollutant concentrations and direct control costs. The Control Strategy Model provides sufficient information to evaluate the regional impact of selected strategies from the standpoint of: (1) the types of sources affected by the strategy; (2) the degree to which these sources are affected in terms of control costs; (3) the resulting change in pollutant emissions; and (4) regionally aggregated values of control costs by source category, total reduction in pollutant emissions, changes to regional fuel-use patterns, and resulting air quality levels.

Regional Economy Model

The purpose of a Regional Economy Model is to provide the Program with a means of assessing economic impacts in a region that contains industries required to invest in air pollution control measures.

In deciding upon production plans, industries traditionally have not had to consider the external social costs generated by their activities. Were they required to do so, they would notice an increase in the costs of production, perhaps to a prohibitive degree. In particular, industries emitting harmful pollutants into the air during the production process have, by not bearing the cost of the resulting social damage, enjoyed the advantages of lower productions costs. With the additional concern for air quality, industries will be encouraged to control the amount of pollutants that they discharge into the air. To industry this means that, for the same amount of output produced prior to consideration of air pollution controls, production costs will be increased as a result of the required investments and operating expenses for air pollution control. Thus, certain economic sectors that in the past have enjoyed the advantages of low-cost production may have to face some degree of economic decline due to the effects of air pollution control strategies.

The Regional Economy Model draws upon four basic types of information in its economic estimation process:

- Average annual cost for air pollution control equipment for each control strategy, including all initial and on-going costs, annual costs of fuel changes and associated equipment change-over costs, less by-product revenues.
- National industry output data and projections (by Standard Industrial Classification code).
- Initial-period regional activity level and capital stock data.
- Regional air quality control strategy variables, such as tax credits.

Given these sets of data, the model produces estimates of regional economic variables, including:

- Gross regional product.
- Employment change by industry.
- Investment change and capital stock by industry.
- Industry value-added.
- Regional tax receipts.

- Regional unemployment.

As a result of a calibration process, estimates can be made of the economic impact resulting from the additional industry investments in air pollution control measures. Figure 7 summarizes the overall economic impact of a maximum control technology strategy. This strategy assumes that every plant invests in the control measures which result in the greatest pollutant emissions reduction.

Program Output

The Program provides the user with a wide variety of output information designed to assist him in developing and evaluating air pollution control strategies. Final decisions may thus be based on a combination of the experience and intuition of the user and the data processing capabilities of the computer simulation.

The simplest output is in the form of reports displaying the contents of the data files. These reports are capable of summarizing the vast amount of data stored in the emission inventory file, control cost file, and regional data file. Figure 8 summarizes pollutant emission rates in the Philadelphia air quality control region. This type of output organizes the vast and detailed information on a region in a format that can be readily assimilated for evaluation and decision processes.

The Atmospheric Diffusion Model provides the user with contour maps, tabular data on average ground-level concentrations, and statistical data on expected maximum concentrations. The tabular data is in the form of a grid system, an arrangement which makes it easy to accurately locate specific receptors in a region. Figure 9 illustrates the ground-level concentration, in the form of a contour map, prior to application of a control strategy. This map represents a sampling of sources (23 points and 30 areas) in the St. Louis air quality control region.

The Control Cost Model provides results showing the types of control measures that are applicable to each type of pollutant source. Along with the control measure identification, the model calculates annual costs and expected emission reduction efficiency as applied to a specific source.

The Control Strategy Model contains the emission standards which, in most cases, require the application of the control measures identified by the Control Cost Model. The outputs illustrate the actual control measures selected for each source, together with the annual costs and data on the degree to which emissions have been controlled. The Model also displays the conversion from emission reductions to reductions in annual and expected maximum ground-level concentrations for selected emission standards. A regional summary, Figure 10, culminates the Programs output and includes a description, by political jurisdiction, of regional costs, regional emission rates, number of sources affected by the control strategy, and figures of merit for each strategy (e.g., cost per ton of pollutant removed, cost per microgram/cubic meter of reduced ground-level concentrations). In addition, a ground level concentration contour map is provided which highlights the effect of the control strategy. The contour map in Figure 11, as well as the tabulated summaries, illustrate a comparison in ground-level concentration before (Figure 9) and after the application of a control strategy to a small sample of stationary sources in the St. Louis region.

The ability of the Program to determine the consequences of specific emission regulations on the basis of computer simulations provides the user with a means for objectively comparing pollution control strategies before they are put into effect. The Program assists the local air pollution control official in selecting, from the large number of control strategy alternatives available to a region, that strategy which will be most effective in solving the region's air pollution problems.

Ideally, the regional air pollution control official is expected to strike a balance between regional expenditures on air pollution control and regional savings resulting from increasing air quality levels. Information on air quality savings (or conversely the costs of air pollution damage) is much scarcer than cost data on air pollution control discussed previously. However, for illustrative purposes the format of a typical cost-benefit relationship is presented in Figure 12. The cost function states the added industrial and power generating costs associated with investments in a maximum sulfur-oxide and particulate matter control technology. This strategy has been applied, via the Program, to 75% of the major point sources of pollution in the St. Louis Region (the line between zero added investment and the $55 million maximum added control costs implies a continuous function through intermediate degrees of control). The benefit function states the added per capita cost resulting from the soiling damages caused by particulate matter pollution. This soiling damage function was previously estimated for the Washington, D. C. area in 1968 by R. Wilson and D. Minnotte of the National Air Pollution Control Administration.

It is clear from this type of diagram that the savings from reducing particulate matter soiling damage alone almost offset the combined costs of maximum sulfur-oxide and particulate matter control. If the added savings of human and animal health, increased yield in vegetation, added visability, and the all-encompassing aesthetic values are added to the savings of soiling damage, then regional air quality savings far out-strip industrial air pollution control costs.

Incidentally, the "optimum" management strategy is represented by a point which balances the marginal utility of additional air pollution control expenditures with additional benefits of air quality. For example, after a point has been reached in both Figures 1 and 12 where the total control costs equal total air quality savings, an additional dollar of control investments may return more than one dollar in air quality benefits.

Unfortunately, quantitative assessments of the benefit-cost functions are still in the future. The control costs and regional economic estimates of these industrial investments are but a first step in the development of these functions. As soon as additional air pollution damage data are evaluated, estimates of benefits will be made along with the estimates of control costs, resulting in more quantitative appraisals of atmospheric resource management strategies.

REFERENCES

1. "Air Quality Criteria for Particulate Matter, Summary and Conclusions," U. S. Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service, February 1969.

2. "Air Quality Criteria for Sulfur Oxides, Summary and Conclusions," U. S. Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service, February 1969.

3. "Control Techniques for Particulate Air Pollutants," U. S. Department of Health, Education and Welfare, Public Health Service, Consumer Protection and Environmental Health Service, January 1969.

4. "Control Techniques for Sulfur Oxide Air Pollutants," U. S. Department of Health, Education, and Welfare, Public Health Service, Consumer Protection and Environmental Health Service, January 1969.

5. Middleton, John T., "Diffusion Modeling for Urban Air Pollution Abatement and Control," presented October 28, 1969, at a Symposium on Multiple Source Urban Diffusion Models, sponsored by the University of North Carolina, held at Chapel Hill, North Carolina.

6. Wilson, E. Milton and S. T. Braunheim, "The Application of Systems Analysis to Air Pollution Control Programs," Paper 69-19, presented at the annual meeting of the Air Pollution Control Association, St. Louis, June, 1969.

7. "Human Investment Programs, An Economic Analysis of the Control of Sulphur Oxides Air Pollution," U. S. Department of Health, Education, and Welfare, Office of the Assistant Secretary (Planning and Evaluation), December, 1967.

8. Burton, E. S. and William Sanjour, "A Simulation Approach to Air Pollution Abatement Program Planning," Socio-Económic Planning Science, Vol.4., pp. 147-150, Pergamon Press, 1970.

9. Wanta, R. C., "Chapter 7, Meteorology and Air Pollution," in the book Air Pollution, Second Edition, edited by A. C. Stern 1968.

10. Bowne, N. E., "A Simulation Model for Air Pollution over Connecticut," Journal of the Air Pollution Control Association, 19(8), pp 570-574, 1969.

11. Martin, Delance O. and J. A. Tikvart, "A General Atmospheric Diffusion Model for Estimating the Effects on Air Quality of One or More Sources," Paper 68-148, presented at the annual meeting of the Air Pollution Control Association, St. Paul, Minnesota, June, 1968.

12. Larsen, Ralph I., "A New Mathematical Model of Air Pollution Concentration Averaging Time and Frequency," Air Pollution Control Association Journal, Vol. 19, No.1, January 1969.

ADVERSE EFFECTS ON	ANNUAL MEAN CONCENTRATIONS Sulfur Oxides (micrograms/ cubic meter)	Particulate Matter (micrograms/cubic meter)
Health	115	80
Visibility	285	150
Materials	345	60
Vegetation	85	---

Table 1. Criteria Levels for Sulfur Oxides and Particulates

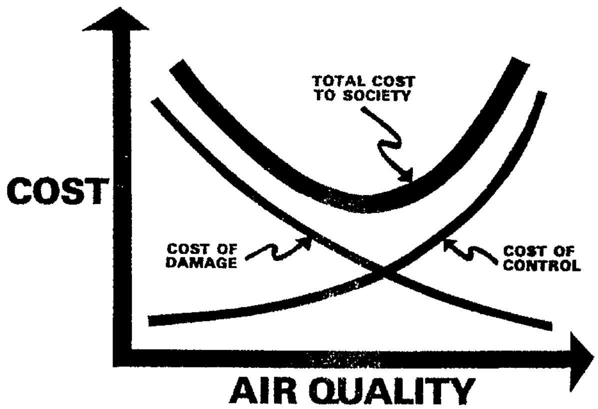

Figure 1. Cost-Benefit Relationship

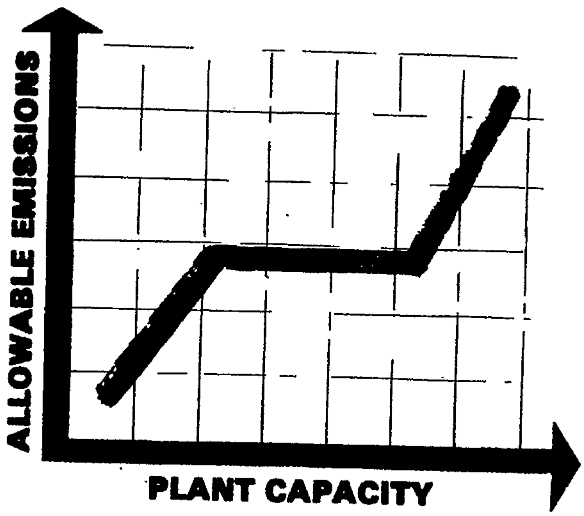

Figure 2. Typical Emission Standard Format.

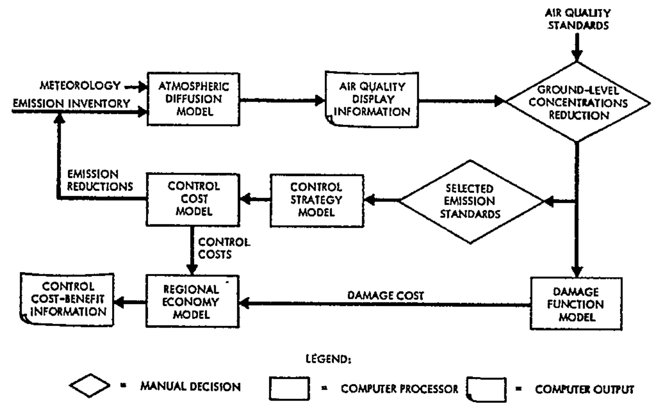

Figure 3. Regional Air Pollution Analysis Program Structure.

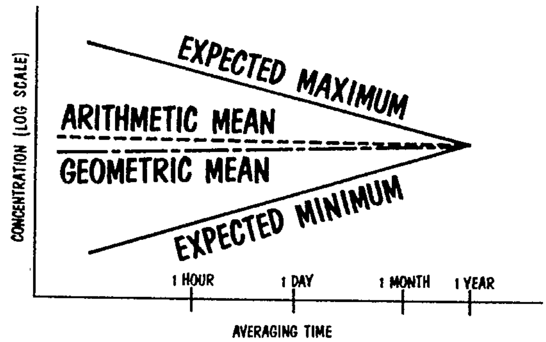

Figure 4. Statistical Distribution of Ground Level Concentrations.

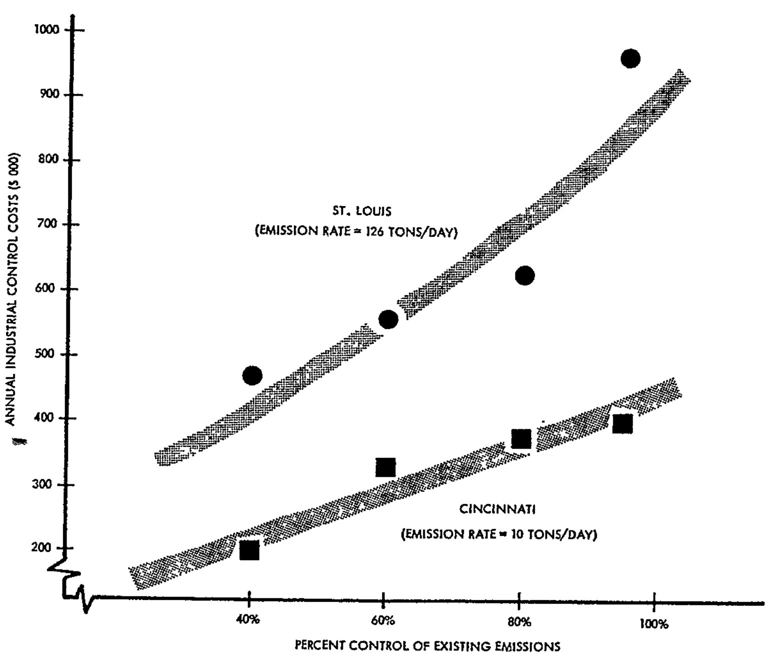

Figure 5. Particulate Matter Control Cost for the Chemical and Allied Products Industry (SIC 28).

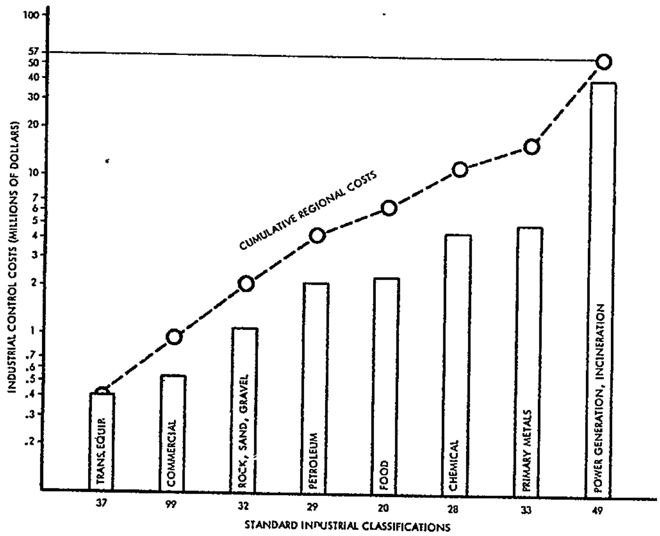

Figure 6. Cost of Maximum Sulfur Oxide and Particulate Matter Control Technology

ST LOUIS - ECONOMETRIC MODEL (1966)

REGIONAL DATA

MAXIMUM CONTROL TECHNOLOGY

REGIONAL EXPENDITURE ($MILLION)	(Y*)* =	6964.734 ,	-0.613 %
CONSUMPTION ($MILLION)	C* =	4418.297 ,	-0.401 %
REGIONAL INCOME ($MILLION)	(Y)* =	7243.336 ,	-0.774 %
EMPLOYMENT BY NON-MANUFACTURING INDUSTRIES (1000)	N-BAR* =	647.3262 ,	-0.477 %
TOTAL EMPLOYMENT (1000)	N* =	933.8894 ,	-0.394 %
TOTAL LABOR FORCE (1000)	L* =	964.7620 ,	-0.358 %
UNEMPLOYMENT (1000)	U* =	34.3381 ,	12.050 %
LOCAL UNEMPLOYMENT RATE (PERCENT)	SMALL U* =	3.5465 ,	12.050 %
ELECTRIC POWER DEMAND FOR RESIDENTIAL USE (1000 KWH)	QC* =	2642.255 ,	-0.634 %
ELECTRIC POWER DEMAND FOR NON-MANUFACTURING INDUSTRIES (1000 KWH)	Q-BAR* =	1935.559 ,	-0.88 %

Figure 7. St. Louis Regional Economic Summary with Maximum Control Technology Investments

POLLUTANT EMISSIONS BY SOURCE CATEGORY (TONS/YEAR)
PHILADELPHIA
06/05/70

POLLUTANT	POLITICAL JURISDICTION	FUEL COMBUSTION	INDUSTRIAL PROCESS	WASTE DISPOSAL	TOTAL
SO2	1	201673	30839	0	232512
SO2	2	157683	18320	0	176003
SO2	3	236655	26751	471	263877
SO2	4	197580	10836	473	208889
	TOTAL	793591	86746	944	881281
PARTICULATE	1	25396	17443	364	43203
PARTICULATE	2	12741	2618	472	15831
PARTICULATE	3	25264	18813	2589	46666
PARTICULATE	4	17309	2948	1275	21532
	TOTAL	80710	41822	4700	127232

Figure 8. Summary of Regional Pollutant Emission Rates

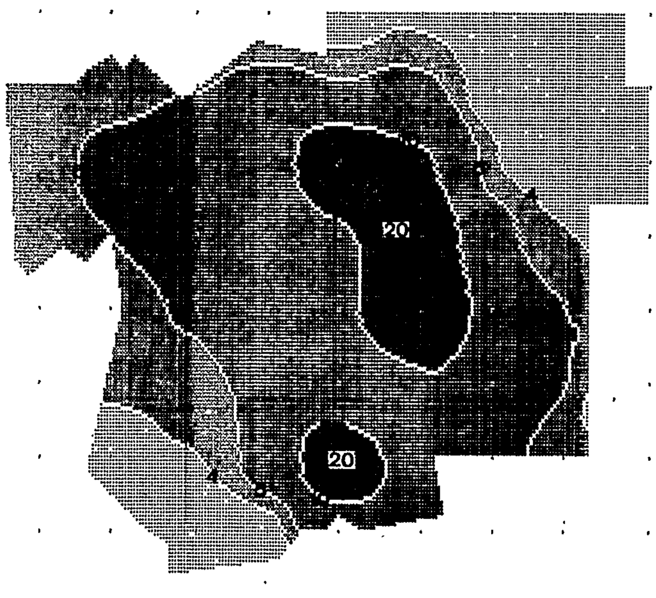

Figure 9. Particulate Matter Concentrations Before Control (Micrograms per Cubic Meter).

INSTALLATION TEST CASE

J U R I S D I C T I O N   S U M M A R Y

ILLINOIS   JURISDICTION

REGULATION TYPE AND NUMBER	TOTAL APPLICABLE POINT SOURCES	TOTAL CONTROLLED POINT SOURCES	EXISTING EMISSIONS FOR POINT SOURCES (TONS/DAY)	EMISSION REDUCTION (TONS/DAY)	ANNUAL CONTROL COST (MILLIONS OF $)	CONTROL COST PER TON REMOVED ($/TON)
FUEL COMBUSTION 1	5	3	41.64	27.13	0.174	17.53
INDUSTRIAL PROCESS 1	7	4	11.40	10.44	0.589	154.68
SOLID WASTE DISPOSAL 1	0	0	0.0	0.0	0.0	0.0
JURISDICTION TOTAL	12	7	53.04	37.57	0.763	55.64

(*) SOME SOURCES COULD NOT ATTAIN THE ALLOWABLE EMISSION
(**) NO DEVICE AVAILABLE TO CONTROL SOME SOURCES.

J U R I S D I C T I O N   E M I S S I O N S

EXISTING EMISSIONS IN TONS/DAY

POINT SOURCES.... 53.0
AREA SOURCES..... 7.5

TOTAL EMISSIONS.. 60.5
TONS/DAY REMOVED.... 37.6

CONTROLLED EMISSIONS IN TONS/DAY

POINT SOURCES.... 15.5
AREA SOURCES..... 7.5

TOTAL EMISSIONS.. 23.0
PERCENTAGE REDUCTION.......62.0 %

J U R I S D I C T I O N   C O N T R O L   C O S T - E F F E C T I V E N E S S

REDUCTION IN TOTAL EMISSION RATE . . . . 55.64 DOLLARS/TON

INSTALLATION TEST CASE

J U R I S D I C T I O N   S U M M A R Y

MISSOURI   JURISDICTION

REGULATION TYPE AND NUMBER	TOTAL APPLICABLE POINT SOURCES	TOTAL CONTROLLED POINT SOURCES	EXISTING EMISSIONS FOR POINT SOURCES (TONS/DAY)	EMISSION REDUCTION (TONS/DAY)	ANNUAL CONTROL COST (MILLIONS OF $)	CONTROL COST PER TON REMOVED ($/TON)
FUEL COMBUSTION 1	3	2	7.09	4.48	0.068	41.29
INDUSTRIAL PROCESS 1	7	4	45.38	44.05	0.300	18.66
SOLID WASTE DISPOSAL 1	1	1	2.55	2.01	0.049	66.33
JURISDICTION TOTAL	11	7	55.02	50.55	0.416	22.57

(*) SOME SOURCES COULD NOT ATTAIN THE ALLOWABLE EMISSION
(**) NO DEVICE AVAILABLE TO CONTROL SOME SOURCES.

J U R I S D I C T I O N   E M I S S I O N S

EXISTING EMISSIONS IN TONS/DAY

POINT SOURCES.... 55.0
AREA SOURCES..... 16.1

TOTAL EMISSIONS.. 71.1
TONS/DAY REMOVED.... 50.5

CONTROLLED EMISSIONS IN TONS/DAY

POINT SOURCES.... 4.5
AREA SOURCES..... 16.1

TOTAL EMISSIONS.. 20.6
PERCENTAGE REDUCTION.......71.1 %

J U R I S D I C T I O N   C O N T R O L   C O S T - E F F E C T I V E N E S S

REDUCTION IN TOTAL EMISSION RATE . . . . 22.57 DOLLARS/TON

INSTALLATION TEST CASE   03/19/70

C O N T R O L   S T R A T E G Y   S U M M A R Y

R E G I O N A L   E M I S S I O N S

EXISTING EMISSIONS IN TONS/DAY

POINT SOURCES.... 108.1
AREA SOURCES..... 23.6

TOTAL EMISSIONS.. 131.7
TONS/DAY REMOVED.... 88.1

CONTROLLED EMISSIONS IN TONS/DAY

POINT SOURCES.... 19.9
AREA SOURCES..... 23.6

TOTAL EMISSIONS.. 43.5
PERCENTAGE REDUCTION.......66.9 %

R E G I O N A L   C O N T R O L   C O S T - E F F E C T I V E N E S S

REDUCTION IN TOTAL EMISSION RATE . . . . 36.67 DOLLARS/TON
REDUCTION IN GROUND LEVEL CONCENTRATION . . . 364742.81 DOLLARS/MICROGRAM/CUBIC METER

Figure 10. Regional Control Cost-Effectiveness Summary.

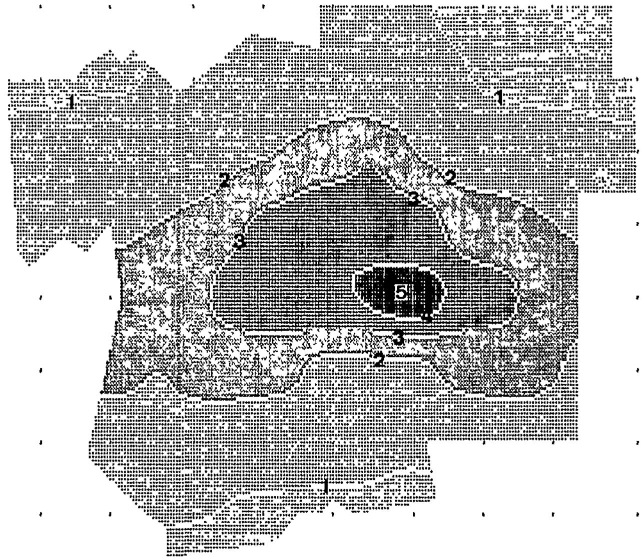

Figure 11. Particulate Matter Concentrations After Control (Micrograms per Cubic Meter).

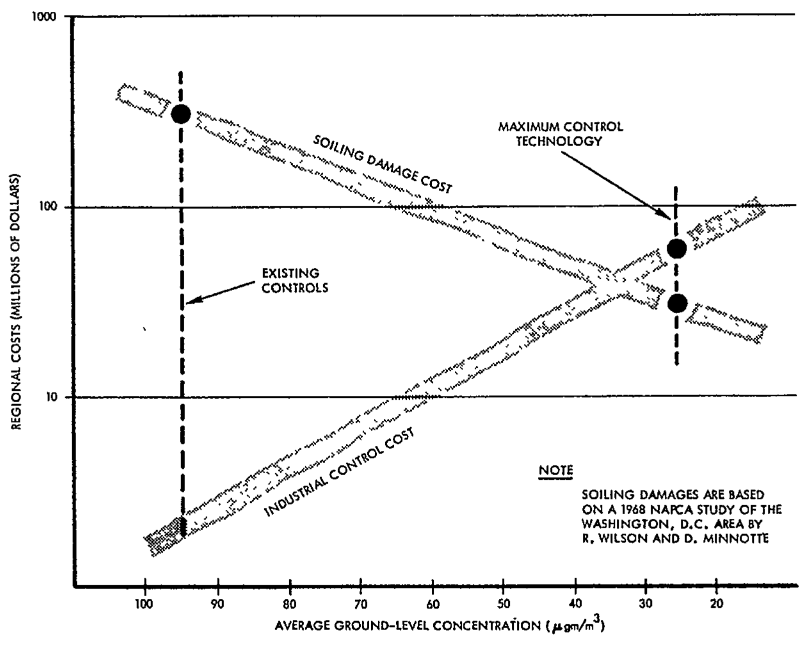

Figure 12. Air Pollution Control Cost Versus Air Quality Benefits