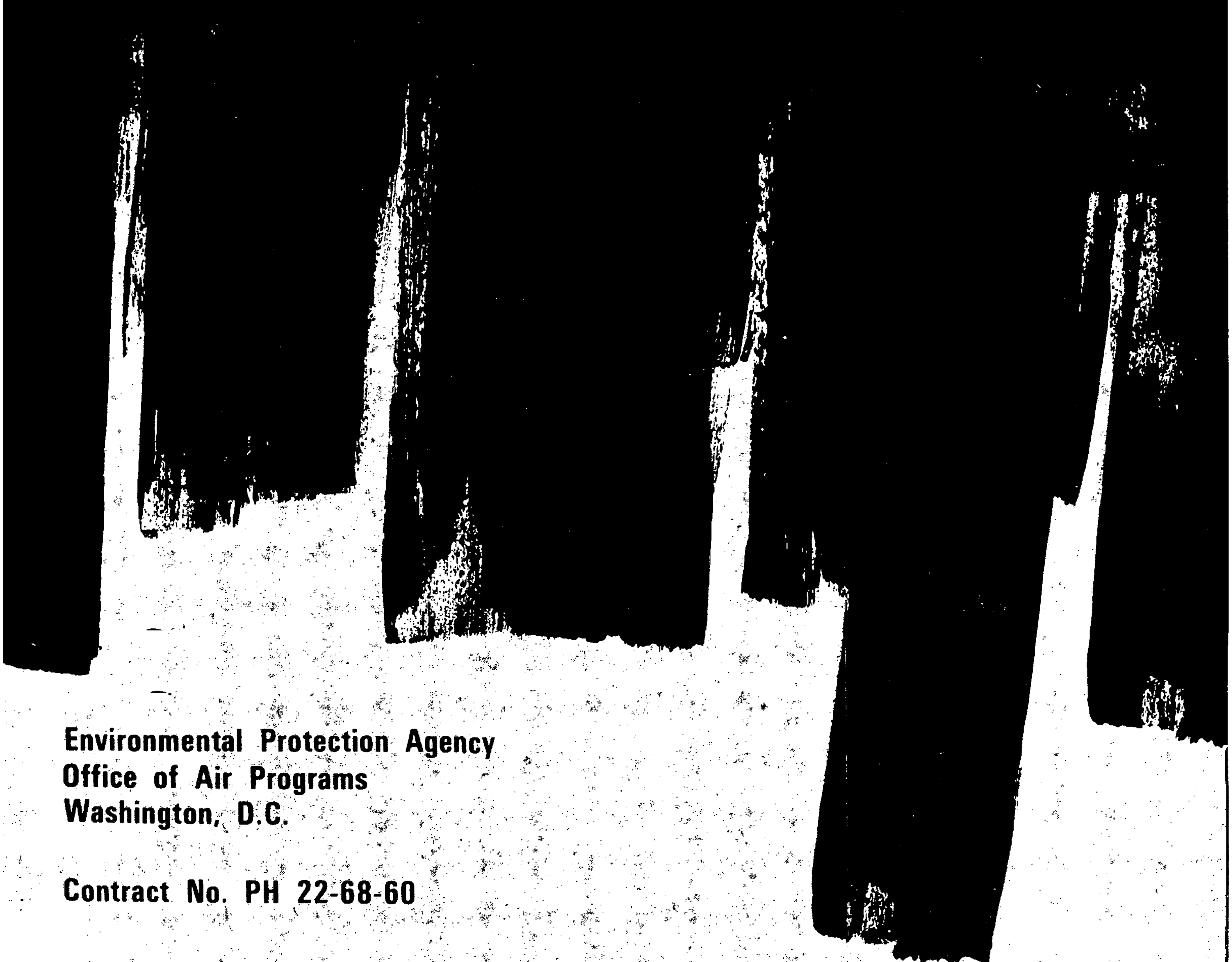
June 1971

Controlling Air Quality St. Louis Case Study



Environmental Protection Agency
Office of Air Programs
Washington, D.C.

Contract No. PH 22-68-60

TRW SYSTEMS GROUP
WASHINGTON OPERATIONS

11130-W002-R0-00

CONTROLLING AIR QUALITY;
ST. LOUIS CASE STUDY

S. E. Plotkin
D. H. Lewis

June 1971

Prepared for

Environmental Protection Agency
Air Pollution Control Office

Contract No. PH 22-68-60

TRW SYSTEMS GROUP
7600 Colshire Drive,
McLean, Virginia 22101

The work upon which this
publication is based was performed
pursuant to Contract No. PH 22-68-60
with the Air Pollution Control Office,
Environmental Protection Agency.

TABLE OF CONTENTS

Page

1.0 INTRODUCTION 1

1.1 EMISSION CONTROL STRATEGIES 2

1.2 EFFECTS OF CHANGING LAND USE 4

2.0 EMISSION CONTROL STRATEGIES 7

2.1 DISCUSSION 7

2.1.1 Conventional Source Category Strategy 11

2.1.2 Rollback 13

2.1.3 Least-Cost Strategy 17

2.2 METHODOLOGY 19

2.2.1 Models 19

2.2.1.1 Implementation Planning Program 19

2.2.1.2 Least Cost Model 22

2.2.2 Setting Up The Diffusion Model 29

2.2.3 The Three Strategies 31

2.2.3.1 Conventional Source Category Strategy 31

2.2.3.2 Rollback Strategy 37

2.2.3.3 Least-Cost Control Strategy 41

2.3 RESULTS 44

2.3.1 The St. Louis AQCR Today 44

2.3.2 Conventional Source Category Strategy 48

2.3.3 Rollback 52

2.3.4 Cost/Benefit Comparison of Rollback and Conventional Strategies 56

2.3.5 Least-Cost Control Strategy 56

2.4 CONCLUSIONS 62

TABLE OF CONTENTS (CONT'D)

Page

2.4.1 Rollback Effectiveness 62

2.4.2 Uniform Application of Emission Standards Versus Least-Cost Strategy 64

2.5 RECOMMENDATIONS 65

2.5.1 Rollback and Air Quality 65

2.5.2 Least-Cost Control 68

3.0 EFFECTS OF CHANGING LAND USE 70

3.1 DISCUSSION 70

3.2 METHODOLOGY 74

3.2.1 Review of Modeling Procedure 74

3.2.2 Basis for Procedure 75

3.2.2.1 Multiplicative Property of Diffusion Model 75

3.2.2.2 Additive Property of Diffusion Model 76

3.2.3 Further Details of Procedure 77

3.2.4 Construction of the Emission Source File 78

3.2.5 Setting Up the Diffusion Model 83

3.2.6 Scenarios 85

3.2.7 Model Shortcomings 87

3.3 RESULTS 90

3.3.1 Where to Locate a New Power Plant 90

3.3.2 Dispersal of Industry 89

3.3.3 Comparison of Diffusion Model Results With Those of Section 2 95

TABLE OF CONTENTS (CONT'D)

Page

3.4 CONCLUSIONS 97

3.4.1 Where to Locate a New Powerplant 97

3.4.2 Dispersal of Industry 99

3.5 RECOMMENDATIONS 100

4.0 REFERENCES 102

APPENDIX A - SOURCE DECK LISTING FOR THE LEAST-COST MODEL 103

TABLES

		Page
2-1	Constraints on Source Emission Control Levels................	27
2-2	Breakdown of Area Source Emissions, St. Louis AQCR...........	36
2-3	Input Data for Sources Controlled Under the Least-Cost Strategy...	40
2-4	St. Louis AQCR - Existing Conditions.........................	45
2-5	St. Louis AQCR - Results of Conventional Source Category Strategy..	49
2-6	St. Louis AQCR - Results of Rollback Strategy................	53
2-7	Least-Cost Strategy Impact on Controlled Particulate Sources..	60
2-8	Least-Cost Strategy Impact on Air Quality....................	61
3-1	Dummy Source File..	79
3-2	Emission Sources to be Relocated.............................	86
3-3	Strategy 10 - Maximum Dispersal of Point Sources.............	88
3-4	Where to Locate a New Power Plant; Air Quality Results........	91
3-5	Where to Locate a New Power Plant; Number of Receptors in Different Ranges of Air Quality...........................	92
3-6	Dispersal of Industry; Air Quality Results...................	93
3-7	Dispersal of Industry; Number of Receptors in Different Ranges of Air Quality.......................................	94
3-8	Comparison of the Two Diffusion Models.......................	96

FIGURES

		Page
2-1	St. Louis Air Quality Control Region	9
2-2	IPP Flow Chart	20
2-3	Diffusion Model Receptor Grid	30
2-4	Allowable Particulate Emissions Based on Input Heat Capacity	32
2-5	Allowable Particulate Emissions Based on Industrial Process Weight	33
2-6	Potential Emissions Standard	34
2-7	Receptor Locations for the Least-Cost Model	43
2-8	St. Louis AQCR Existing SO_2 Ground Level Concentrations	46
2-9	St. Louis AQCR Existing Particulate Ground Level Concentrations	47
2-10	St. Louis AQCR - SO_2 Ground Level Concentrations After Imposition of Conventional Source Category Strategy	50
2-11	St. Louis AQCR - Particulate Ground Level Concentrations After Imposition of Conventional Source Category Strategy	51
2-12	St. Louis AQCR Particulate Ground Level Concentrations After Imposition of Rollback Strategy	54
2-13	St. Louis AQCR - SO_2 Ground Level Concentrations After Imposition of Rollback Strategy	55
2-14	SO_2 Cost and Benefit Curves	58
2-15	Particulate Cost and Benefit Curves	59
3-1	St. Louis Study Area	73
3-2	Prediction Model Flow Chart	77
3-3	Location of Dummy Sources	82
3-4	Diffusion Model Receptor Net	84
3-5	Diffusion of Pollutants from a Point Source	98

1.0 INTRODUCTION

This report addresses two major questions in air pollution control:

- What emission control strategy should be used by the states to achieve their air quality goals?
- How can air quality effects of changing land use patterns be predicted?

The report presents a comparison of three alternate emission control strategies as applied to the St. Louis Air Quality Control Region. The strategies are:

- A conventional set of emission source-category standards.
- A Rollback strategy
- A Least-Cost strategy.

The conventional strategy is used as a control from which to evaluate the Rollback and Least-Cost strategies. Study results include regional costs, air quality achieved, emission reductions, plots of pollutant concentration levels (isopleths), and a measure of "benefit."

In addition, the report presents a description and brief analysis of a simple procedure by which a diffusion model can be used to predict the (air quality) consequences of shifting land use, without incurring the considerable expense of continually re-running the entire model. The procedure is used to analyze the effects of two scenarios in the St. Louis AQCR:

- A large new powerplant is added to the region.
- Industry is dispersed to the suburbs.

1.1 EMISSION CONTROL STRATEGIES

Volume 36, Number 67, of the Federal Register (April 17, 1971) proposes that, in order to comply with the Clean Air Act, each state must submit to the Environmental Protection Agency a control strategy for each national ambient air quality standard, and must demonstrate that the strategy is adequate for attainment of each standard. The criteria for "demonstration of adequacy" is the use of either a diffusion model or a proportional ("Rollback") model.

The Rollback model is a means of defining regional emission control needs in the absence of diffusion modeling, or when attempts at correlating model predictions and actual air quality measurements fail. The model defines a required percentage reduction (rollback) in total regional emissions as the basis for achieving a desired air quality goal; the magnitude of the reduction is based on the difference between the air quality goal and the current air quality as detected by air pollution measuring stations. As discussed in Section 2.1, such a reduction in emissions does not guarantee attainment of the air quality standard, because the model does not specify how the emission reduction is to be attained. Nevertheless, it may be expected that a large number of states will select a Rollback strategy. This report therefore attempts to show whether an appropriately constructed Rollback strategy will achieve the desired air quality. A discussion of different available strategies is presented, and an "ideal" strategy is selected and implemented. The Rollback Strategy cost and effectiveness is compared to that of a conventional control strategy which achieves the defined air quality standard.

The conventional and Rollback control strategies presented in the report are both based on the premise that it is inequitable and politically infeasible to apply emission standards which vary with plant location within a political jurisdiction (state, Air Quality Control Region, county, etc.). Thus, both of these strategies control industry located in areas whose air quality is above the standard as stringently as those located in air quality trouble spots. However, it should be clear that the price of this uniformity is an added cost which does not contribute to attaining the air quality standard. These costs are defined in this report by comparing the conventional strategy to a Minimum Regional Cost strategy achieved by utilizing a Linear Programming Model. In this strategy, emission sources are controlled only when they strongly contribute to a violation of the air quality standard. In addition, control is optimized so that the least cost is imposed on the region. The "least-cost" strategy defined by the Linear Programming Model attains the desired air quality standard at a considerable savings in control costs to the region's industries. However, the patterns of pollutant concentration throughout the region "flatten out," that is, there are more areas where air quality is just at or slightly below the standard than would be the case in a uniformly applied emission control strategy. The "overcontrol" which is achieved in some areas by a uniform strategy may be judged desirable because it leaves the region with greater flexibility for continued industrial growth. Thus, the savings of a "least-cost" strategy must be balanced by its added pollution burden to the region.

1.2 EFFECTS OF CHANGING LAND USE

Diffusion modeling is normally used to predict the existing air quality in a region given the existing emission sources and their locations. The nature of the diffusion model allows it to be used as a predictive tool also, since the emission source file used in the model can be altered to reflect the shutdown or alteration of sources, the shifting of their locations, or the addition of entirely new sources*. Since a full scale diffusion model run requires a very substantial amount of computer time (normally several hours on an IBM 360-40) and is thus extremely expensive, an analysis investigating several land use alternatives becomes somewhat impractical if the model must be rerun for every alternative.

It is extremely important, however, to be able to predict the effect on air quality of changing land use. Although pollution control strategies being promulgated now should reduce ambient air quality to acceptable standards, continued economic growth can cause concentration levels to rise back above these levels (even with National Emission Standards for new industrial plants). Predictive tools are needed to place new plants in areas which can sustain them without violating

---

*However, any changes of location of sources will result in some degradation of the calibration of the model, since the calibration, which corrects for topography in relation to plant locations is based on the original configuration of sources.

standards, and to evaluate different land use plans so as to minimize future pollution levels.

The procedure presented here for using the diffusion model as a convenient predictive tool utilizes the linear qualities of the diffusion model. The diffusion model is run once with an emission source file consisting of all the sources presently existing in the region, plus a number of "dummy sources"--area and point sources with miniscule emissions. A new air quality "map" of the region can then be reproduced, without rerunning the diffusion model, while scaling any source's emission up or down. Sources can therefore be made to disappear, or appear (if they were "dummies" in the first run), or grow...utilizing a simple program which requires only a few minutes of computer time. The model used in this study was the Control Strategies Segment of the Implementation Planning Program (IPP) and is thus more complex than is necessary given a separately developed program.

The purpose of this report is three-fold:

- To present the prediction procedure.
- To present the results of two "scenarios" produced by the procedure.
- To describe the shortcomings of the procedure and define what can be done to overcome them.

The limited nature of the model demonstration prevented any conclusive estimate of the efficacy of the prediction procedure to be made at this time. The scenario results indicate that the addition to a region of a powerplant with a very tall stack does not make a strong local impact on an average annual" basis, a conclusion which agrees with expectations. The "dispersal of industry" scenario illuminated some mild possibilities for air quality improvements by shifting emission source locations, but the results were definitely not clear cut and deserve further study. Recommendations are made in Section 3.5 for investigating the accuracy of the defined air quality prediction procedure; it is felt that the potential value of such a procedure warrants such additional study.

2.0 EMISSION CONTROL STRATEGIES

2.1 DISCUSSION

The purpose of this section is to examine three kinds of strategies for achieving a region's air quality goals. These strategies are:

- A conventional set of emission source-category standards
- A Rollback strategy
- A least-cost strategy

The examination is designed to answer two questions:

- Will a well-constructed Rollback strategy achieve its air quality goal?
- What price does a region pay for applying emission standards uniformly, without regard to plant locations?

As noted in the Introduction, it is highly probable that many states will select Rollback strategies for their air quality implementation plans. The use of such strategies does not guarantee that the designated air quality standards will be met, because the reduction in total regional emissions specified by Rollback will not necessarily achieve the same reduction in ground level pollutant concentrations (air quality).

The failure of a Rollback strategy could have serious consequences for a state. A further stiffening of the emission standards could be more expensive than the accompanying reduction in emissions and improvement in air quality would warrant ... because the industrial plants, incinerators, and power plants being controlled would have already installed expensive pollution control devices which might have to be removed and replaced with more efficient devices, at a total cost possibly far in excess of what would have been spent installing the more efficient equipment in the first place. It is therefore important that Rollback be able to achieve the stated air quality goal without a process of trial and error.

This study attempts to show whether or not a Rollback strategy will achieve its stated air quality goal given:

- A goal which is known to be reasonable
- A set of emission standards which are equitable to the controlled industries and which will cause a reasonably uniform reduction in emissions throughout the region.

The St. Louis Air Quality Control Region (Figure 2-1) is used as a test area. Pollutants examined are SO_2 and particulates. A set of source-category emission standards similar to those in the 305(a) Cost of Clean Air Report to Congress is applied to the region in order to establish a control case with which to compare Rollback strategy. The air quality goals set for the strategy are those achieved by the control, thus assuring that the goals are attainable (the method used in arriving at an air quality goal has nothing in common with the conventional procedure, which is to base such goals on the known effects of different air quality levels). The modeling tool used is the Implementation Planning Program, which predicts the air quality, emission reductions, and costs resulting from the application of emission control standards. Besides comparing figures of merit produced by IPP (air quality, cost-effectiveness, total cost), a "cost/benefit" comparison of the two strategies is made using a Regional Cost/Benefit Model (Reference 3) developed in parallel with this study. The model utilizes a pro forma linear damage function which

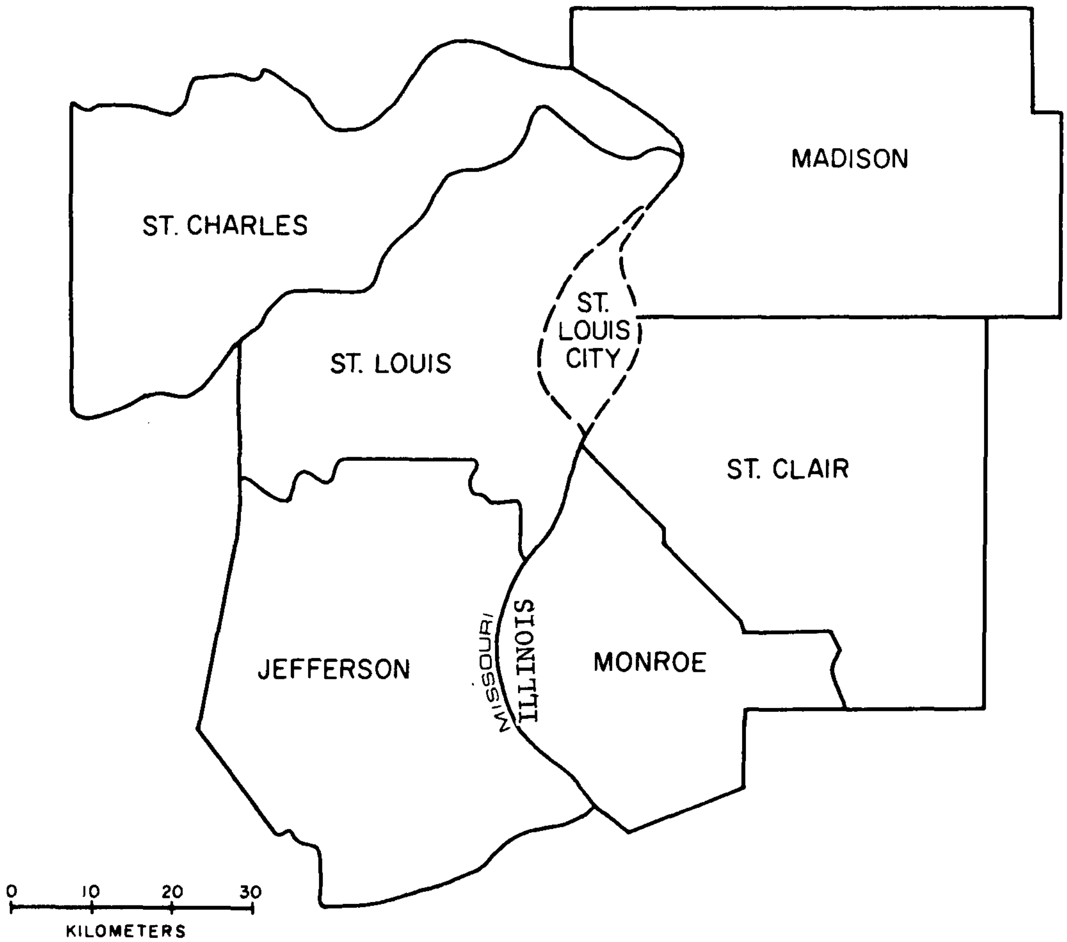


Figure 2-1.

St. Louis Air Quality Control Region

relates total damages per capita from all direct effects of pollution to regional air quality.

Neither the Rollback nor the 305(a)-based source-category emission strategies consider source location as a determinant of allowable emission levels for industrial plants. Given two identical plants in the same political jurisdiction, one of which is located in the urban core area and is contributing heavily to an air pollution problem, the other located outside the core area in a "clean air" district...a source-category emission standard requires both plants to control to identical levels. If the attainment of an air quality standard is defined as that situation where no location in the region has a ground level pollutant concentration above the specified limit, then obviously this uniform method of control is not the most efficient way to achieve "air quality"...the most efficient, or least-cost method would be to vary control requirements so as to impose the heaviest controls on those plants most affecting concentrations at locations where the standard is violated, while allowing those plants which do not contribute to air quality violations to remain uncontrolled.

In this analysis, a least regional cost strategy for particulate control is identified. The strategy is based on the selective control of the 27 largest emission sources in the region according to their relative contribution to ground level concentrations at receptors where air quality standards are violated. A linear programming model is used to apply control devices to these sources to attain an air quality standard at selected receptors identical to that achieved by the source-category strategy, allowing a direct comparison between the alternative control schemes to be made.

2.1.1 Conventional Source Category Strategy

The first of the three emission control strategies compared in this report, the Conventional Source Category Strategy, is used essentially as a control from which to evaluate the Rollback and Least Regional Cost Strategies. The air quality achieved by the "conventional" strategy, as measured by the atmospheric diffusion model of the Implementation Planning Program (Section 2.2.1.1), is used as the "goal" for the Rollback and Least Cost Strategies so as to provide a clear basis for comparison of the strategies.

The Conventional strategy is quite similar to that used in the 305(a) Cost of Clean Air Report to Congress; it consists of the following emission standards:

- Particulate Fuel Combustion Sources - HEAT INPUT STANDARD
- Particulate Industrial Process Sources - PROCESS WEIGHT STANDARD
- Particulate Solid Waste Disposal Sources - POTENTIAL EMISSION STANDARD
- SO_2 Fuel Combustion Sources - EQUIVALENT FUEL SULFUR LIMIT
- SO_2 Industrial Process Sources - EXHAUST CONCENTRATION STANDARD

Although the Process Weight Standard and Exhaust Concentration Standard are common control measures, they both have serious shortcomings. The Process Weight Standard penalizes industries and processes which are conservative of raw materials, and inversely rewards those which use large quantities of raw materials, by allowing higher emission rates for higher process weights with no regard to the actual physical output, in finished goods, of the plant. The Exhaust Concentration Standard disregards the fact that the only sensible measure of emissions is the actual amount of pollutant leaving the stack, and not the relative dilution of that pollutant in the exhaust gas. Since some types of processes naturally produce more exhaust gas than others, the Concentration Standard favors these sources over those which produce similar amounts of pollutants but have lower exhaust gas production.*

* A justification for this "favoritism" is that the cost of control devices varies directly with exhaust gas rate, so that the high (gas) volume plant would incur far greater expense to control to the same efficiency as the low-volume plant. However, this variation of control device cost is certainly not accounted for by an allowable concentration which is the same regardless of gas rate; at the least, a concentration which varies with gas rate might be used.

2.1.2 Rollback

Rollback is a means of defining regional emission control needs in the absence of diffusion modeling, or when attempts at correlating model predictions and actual air quality measurements fail. Rollback defines the net reduction in total regional emissions needed to satisfy a given air quality standard; the reduction R is calculated by the formula:

$$R = \frac{X_{max} - X_{standard}}{X_{max} - X_{background}}$$

where X = ground level concentration ("air quality") of a given pollutant

X_{max} = existing air quality at the location having the highest measured or estimated concentration in the region

$X_{standard}$ = air quality standard

$X_{background}$ = background concentration

Although it is implicitly assumed that the reduction R will achieve the desired air quality level, the actual resulting air quality may be considerably better or worse than the standard, depending upon the means chosen to implement Rollback. For instance, it is possible to concentrate on reducing emissions from an area's powerplants (which traditionally produce a significant portion of total regional emissions) yet not affect air quality in the urban core areas where the major problems exist. On the other hand, if reductions are concentrated geographically in and around the pollution "peak" areas, Rollback requires a more severe reduction than is really necessary.

A desirable rollback strategy should have the following characteristics:

1) It should be equitable. Industries should not be penalized for prior attempts at controlling emissions, nor should certain emission sources be controlled severely while others escape control.

2) If the level of control is varied geographically, the areas of maximum severity should be those which have an air quality problem. Otherwise, severity of control should be uniform throughout the area.

The conceptually simplest method of applying rollback is to require all pollution sources in the region to reduce their emissions by the factor R. Although this strategy is certain to achieve the desired air quality*, it is not used because of its gross inequity. Industrial facilities which have taken steps to control their pollution prior to any legal requirements are penalized for this action, since they must reduce their already controlled emissions by the same percentage that is applied to the uncontrolled polluter...and cost-effectiveness of pollution control devices decreases as the total degree of control increases. Furthermore, plants which are already utilizing extremely high efficiency devices will not be able to comply with added reduction requirements, forcing legal penalties upon the most (rather than the least) conscientious industries. One concludes from this example that a good strategy would give credit to:

- The use of emission control devices.
- The burning of "clean" fuels.

*Because such a uniform reduction will automatically reduce ground-level concentrations (over the background level) at EVERY POINT IN THE REGION by the same factor R.

- An initial investment in a "clean" process or piece of equipment.

Certain types of emission standards satisfy this condition very well and are particularly suited for rollback applications. For instance, a Potential Emissions Standard bases the emission rate a plant is allowed not on its present emission rate, but instead on that rate it would have if its controls were removed. As an example, Plant A and Plant B are identical except that Plant A has installed an electrostatic precipitator with efficiency of .90 to control its particulate emissions, while Plant B's emissions are uncontrolled; a standard which requires 85 percent control of potential emissions is applied to both plants. The allowable emissions from the two plants are the same; however, Plant A is within the law, since it already controls its potential emissions by 90 percent, and thus it incurs no additional expense; Plant B, on the other hand, must purchase a control device of at least 85 percent efficiency.

Although the Potential Emission Standard (PES) is a generally equitable* standard for industrial process emission sources, it is not satisfactory,in its present form, for application to fuel combustion sources (boilers). In the case of sulfur dioxide emissions, a PES does not account for those sources burning low sulfur fuels, i.e., a plant burning low sulfur fuel would be allocated a smaller allowable SO_2 emission than an identical plant burning high sulfur fuel. A more equitable emissions standard would be an "Equivalent Low Sulfur Fuel Standard," which requires either the use of fuels containing less than a specified percent of sulfur by weight, or else the installation of a flue gas desulfurization device yielding an equivalent controlled SO_2 emission rate. PES's have the same limitation

*An exception: When two plants of identical capacity use different processes, one of which is "cleaner" than the other.

with respect to low ash-content fuels for particulate emission controls. In addition, the standards do not account for the wide range of particulate emission factors from coal combustion. For example, potential emissions from a wet bottom boiler with reinjection are nearly twice as high as those from a similar type boiler without reinjection; thus, the operator who initially chose the cleaner equipment would be required by a PES to reduce his emission rate to a considerably lower level than that required of the "dirtier" operator.

One means of giving "credit" to the operator of a clean plant is to calculate potential emissions on the basis of an "average plant" rather than the actual plant, using some measure of plant size such as kilowatts/hour produced (for powerplants), etc. Thus, the allowable emission rate depends only on plant size and not upon previously installed controls, fuel types, or boiler types. A commonly used emission standard which duplicates the effect of such an "improved" PES is the Heat Input Standard; this standard specifies an allowable emission rate on the basis of the maximum BTU input to a fuel combustion plant. Since specification of a model plant would require the definition of a relationship between potential emissions and heat input (or some other measure of plant size), the "x axis" of the Heat Input curve could easily be changed from BTU/hour to Potential Emissions; thus, the two standards are interchangeable.

In summary, we may define a "Rollback Strategy" for controlling SO_2 and particulates as follows:

- Particulate Fuel Combustion Sources - HEAT INPUT STANDARD
- Particulate Industrial Process Sources - POTENTIAL EMISSIONS STANDARD

- Particulate Solid Waste Disposal Sources - POTENTIAL EMISSIONS STANDARD
- SO_2 Fuel Combustion Sources - EQUIVALENT FUEL SULFUR LIMIT
- SO_2 Industrial Process Sources - POTENTIAL EMISSIONS STANDARD

This strategy satisfies the above definition of "equity". It remains to be shown whether or not the strategy will achieve the air quality standard selected for the region.

2.1.3 Least-Cost Strategy

Both the Conventional source category strategy and the Rollback strategy described in the preceeding sections apply emission standards to each of three categories of emission sources: fuel combustion, industrial process, and solid waste disposal sources. Smaller plants are typically given a break when these emission standards are designed, but all plants of given size and type are treated equally. In other words, an integrated iron and steel plant in the central business district of a given region would be required to control to the same level as a steel plant of the same size located in the outskirts of that region. This ignores the fact that the suburban plant is not likely to be contributing to an air quality violation to the same extent as the centrally located plant.

The Least-Cost Control Strategy tries to overcome this deficiency by recognizing the dependence of air quality on plant locations (i.e., on meteorology and topography). Individual point sources are controlled to a level which depends upon how much they contribute to pollutant concentrations above the air quality standard. Intuitively, this should be a cheaper control technique, at least from the regional point of view. The difference between the cost associated with the conventional or rollback source category control strategies and the least-cost control strategy is an indication of what it is costing the region to maintain the equity treatment of plants implicit in a source category strategy.

It should be noted that this additional "equity" cost allows the maintenance of a level of air quality in certain areas which is considerably better than that which would be obtained with the least-cost strategy. The "over control" caused by the source category strategies provides a cushion for further industrial and residential development. If the region is controlled only to where the air quality standard is barely met at all points, then the addition of any new emission sources will cause an air quality violation; thus, the least-cost strategy might restrict a region's flexibility as far as locating new development is concerned.

The strategy that is developed in this study controls particulate emissions from 27 major point sources in the St. Louis AQCR. The air quality standard used as a constraint is that attained by the conventional source category strategy, thus allowing a clear comparison between these two different strategy types.

2.2 METHODOLOGY

2.2.1 Models

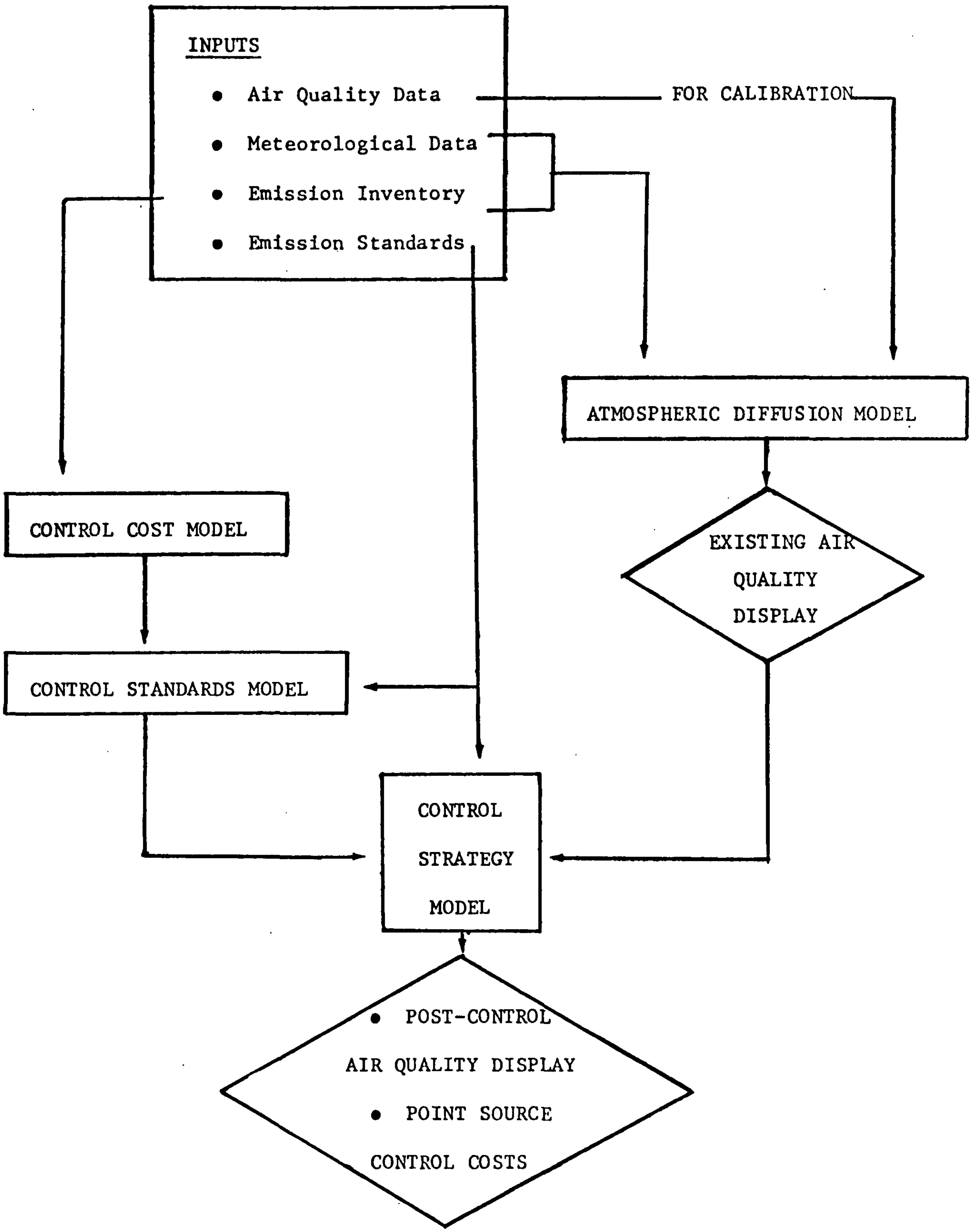
2.2.1.1 Implementation Planning Program

The Implementation Planning Program (IPP) is a series of models developed by TRW under contract to APCO which help in the evaluation of alternative strategies for control of air pollution sources. A flow chart of the program is illustrated in Figure 2-2.

The heart of IPP is the atmospheric diffusion model, which predicts expected regional ambient concentrations of pollutants by mathematically simulating the dispersion of these pollutants throughout the region. The inputs to this model are a detailed emission inventory, various meteorological data, and measured pollutant concentration data. The emission inventory lists individually the major sources of pollutants (power plants, incinerators, etc.) and describes in detail those parameters which characterize the sources and their emissions. The inventory also characterizes those emission sources which are too small to be identified individually by aggregating them to form "area sources." The meteorological data includes wind speed and direction, mixing depth, and other phenomena which describe the transport mechanism which carries the pollutants from the sources throughout the region. The measured concentration data is used to calibrate the theoretical model, in order to account for inaccuracies in the diffusion equation, inaccurate source emissions and meteorological data, irregularities in the area's topography (the diffusion equation assumes a flat plain), and other errors.

Besides predicting present air quality conditions, IPP can predict the effects of a pollutant control "strategy" (a series of emission control standards which apply to all major sources in the area) on the area's

Figure 2-2 IPP Flow Chart



air quality and measure the resulting pollution control device demand and cost. This is accomplished by a control cost, a control standards, and a control strategy model.

The control cost model assigns to each major source all those control devices which may reasonably be used for reducing emissions. Devices for the control of particulates are generally applied to the outlets of the polluting process (usually the stacks). Sulfur dioxide control is usually accomplished by switching to low sulfur fuels or by the use of flue gas desulfurization techniques. The model's output consists of lists of device names, their efficiencies and costs, and their effects on pollutant emissions, for each major emission source.

The control standards model applies a series of emission standards to the three categories of emission sources: fuel combustion, industrial process, and solid waste disposal sources. Output consists of a list, for each major source, of the applicable standards, their prescribed allowable emissions, suitable control devices selected on the basis of effectiveness and least cost (one device for each standard), and the cost and effect on emission of the devices (obtained from the control cost model).

The control strategy model calculates the effects of applying selected sets of three emissions standards (two in the case of SO_2) to every political jurisdiction in the control area. Selecting the applicable results from the control standards model, the model develops a picture of the change in emissions (and costs) resulting from a realizable pollution control alternative. Using the output of the atmospheric diffusion model, the strategy model recomputes the pollutant concentration distribution resulting from the new emission pattern, thus allowing a decision to be made on the effectiveness of the strategy based on both the resulting costs (on a regional, industry-by-industry, political jurisdiction-by-political jurisdiction, or source-by-source basis) and the actual air quality produced by implementation of the standards.

2.2.1.2 Least Cost Model

The purpose of the Least Cost Model is to determine a set of point source emission reductions which will achieve a stated air quality standard at the least total control cost to the region.

Basically, the model relates, via a set of transfer coefficients obtained as an output from the IPP Air Pollutant Concentration Model (Diffusion Model), the emissions at each source in the region to the ground-level concentration (air quality) at a set of receptors dispersed throughout the region. With this approach, the control of localized pollutant "hot-spots" is achieved, as well as control of the central area of the region. This is particularly important for air quality control regions which include a number of geographically separated centers and industrial areas.

Since source emissions and source-receptor transfer coefficients determine ground-level concentration, the model contains a set of inequality constraints which restrain the ground-level concentration at each receptor location to be less than the value selected as an air quality standard for each geographic subdivision of the region. Long-term (annual or seasonal) average pollutant ground-level concentrations are used, although shorter term averages could be used with the model as formulated, if the appropriate set of transfer coefficients were available.

The model considers the relationship between source control technology, control costs, and control effectiveness at each pollutant source in the region. The IPP Control Cost Segment is used to determine the least-cost source control equipment mix required to obtain given levels of reduction of pollutant emissions, with the assumption that control costs are approximately piecewise-linear. The amount of control to be applied to each source is constrainted to be less than or equal to that which is technologically possible at this time. Additional constraints on the sources may be imposed to insure that a given source achieves a minimum level of emission reduction.

Thus, with the previously mentioned constraints, the model minimizes total direct control costs for the region in the following manner:

Let f_{ijk} (E_{ij}) be the transfer function between the average ground-level concentration (g.l.c.) of the j^{th} pollutant at the k^{th} receptor from the i^{th} source, and let n_i, n_j, n_k be the total number of sources, pollutants and receptors to be considered, respectively. Values of this transfer function are currently computed by the Air Pollutant Concentration Segment for annual averages. The ground-level concentration is then

$$\chi_{jk} = \sum_{i=1}^{n_i} f_{ijk} (E_{ij}). \qquad (1)$$

If χ°_{jk} and χ_{jk} are the g.l.c. of the jth pollutant at the kth receptor before and after control of this source, and E°_{jk} and E_{jk} are the source emission levels of the jth pollutant at the ith source before and after control, then

$$\chi^{o}_{jk} - \chi_{jk} = \sum_{i=1}^{n_i} \left[f_{ijk} (E^{o}_{ij}) - f_{ijk} (E_{ij}) \right] \qquad (2)$$

If the required reduction is defined as

$$X_{ij} = E^{o}_{ij} - E_{ij} \qquad (3)$$

and the usual linearity assumption is applied, i.e.,

$$f_{ijk}(A+B) = f_{ijk}(A) + f_{ijk}(B), \qquad (4)$$

then

$$\chi^{o}_{jk} - \chi_{jk} = \sum_{i=1}^{n_i} f_{ijk}(X_{ij}). \qquad (5)$$

The function of the Control Cost Segment is to make available for each source, i, a unique cost function, C_{ij} (X_{ij}), in the form

$$C_{ij} (X_{ij}) = C_1 + C_2 X_{ij} + C_3 X_{ij}^{2} + \ldots\ldots\, C_n X_{ij}^{n-1}. \qquad (6)$$

This cost function represents the minimum total cost of achieving a reduction of an amount X_{ij} in the emissions of the j^{th} pollutant from the i^{th} source. Thus, for a given set of source control measures $[X_{ij}]$, the total direct cost to the region will be given by

$$C_T = \sum_{i=1}^{n_i} \sum_{j=1}^{n_i} C_{ij} \quad (X_{ij}), \qquad (7)$$

and the corresponding set of ground-level concentration reductions, $[\chi^o_{jk} - \chi_{jk}]$, will be given by equation (3).

At this point, the control strategy, or means of selecting the preferred set of control measures $[X_{ij}]$, is introduced. In general, there are two basic approaches. The required set of control measures may be computed by an input scheme, such as applying an equiproportional emission standard to the relevant sources. For each source requiring a maximum allowable emission level of E^{max}_{ij}, the reduction is expressed by

$$X_{ij} = E^o_{ij} - E^{max}_{ij} \ . \qquad (8)$$

Alternatively, a different set of x_{ij}'s could be computed by some preference criteria. The most widely utilized preference criterion is an economic one, the so-called least total cost to achieve a given air quality standard. Although air quality standards are generally stated in terms of concentration and relative frequency of occurrence, an arithmetic average g.l.c. requirement is always implicit.

Denoting the average g.l.c. required by the standard for the j^{th} pollutant as S_j, and requiring that no receptor within the region have a g.l.c. greater than the given standard, there are constraints on both the least-cost and equiproportional strategy so that

$$X_{jk} < S_j \tag{9}$$

for

$$j = 1,2,\ldots..n_j \tag{10}$$

$$k = 1,2,\ldots..n_k \tag{11}$$

or, substituting in equation (1),

$$X^o_{jk} - f_{ijk}(X_{ij}) < S_j \tag{12}$$

i.e., the existing g.l.c. minus the amount reduced must be less than S_j throughout the region.

Under the assumption that

$$f_{ijk}(X_{ij}) = A_{ijk} X_{ij}, \tag{13}$$

the expanded set of constraints is shown in Table 2-1.

The least-cost strategy requires that

$$C_T = \text{minimum}, \tag{14}$$

subject to the constraints of Equation (12). If the cost functions (which must be minimum cost functions in the sense that they represent a selection from all available source control techniques for achieving a specified reduction) are approximated by linear functions,

$$C_{ij}(X_{ij}) = C_1 + C_2 X_{ij}. \tag{15}$$

TABLE 2-1. CONSTRAINTS ON SOURCE EMISSION CONTROL LEVELS

G.L.C. Before Control		Source 1		Source 2				Source N		G.L.C. After Control	
X°_{11}	-	$[a_{111}x_{11}$	+	$a_{211}x_{21}$	+	...	+	$a_{N11}x_{N1}]$	$\leq$	s_1	POLLUTANT 1, RECEPTOR 1
X°_{12}	-	$[a_{112}x_{11}$	+	$a_{212}x_{21}$	+	...	+	$a_{N12}x_{N1}]$	$\leq$	s_1	POLLUTANT 1, RECEPTOR 2
.		.		.				.		.	.
.		.		.				.		.	.
.		.		.				.		.	.
X°_{1M}	-	$[a_{11M}x_{11}$	+	$a_{21M}x_{21}$	+	...	+	$a_{N1M}x_{N1}]$	$\leq$	s_1	POLLUTANT 1, RECEPTOR M
X°_{21}	-	$[a_{121}x_{12}$	+	$a_{221}x_{22}$	+	...	+	$a_{N21}x_{N2}]$	$\leq$	s_2	POLLUTANT 2, RECEPTOR 1
.		.		.				.		.	.
.		.		.				.		.	.
.		.		.				.		.	.
X°_{2M}	-	$[a_{12M}x_{12}$	+	$a_{22M}x_{22}$	+	...	+	$a_{N2M}x_{N2}]$	$\leq$	s_2	POLLUTANT 2, RECEPTOR M
X°_{31}	-	$[a_{131}x_{13}$	+	$a_{23}x_{23}$	+	...	+	$a_{N31}x_{N3}]$	$\leq$	s_3	POLLUTANT 3, RECEPTOR 1
.		.		.				.		.	.
.		.		.				.		.	.
.		.		.				.		.	.
X°_{3M}	-	$[a_{13M}x_{13}$	+	$a_{23M}x_{23}$	+	...	+	$a_{N3M}x_{N3}]$	$\leq$	s_3	POLLUTANT 3, RECEPTOR M

the problem is amenable to solution by linear programming techniques. The source deck listing for the Least-Cost Model is presented in Appendix A. This Model was developed on the TRW Timeshare System (based on a CDC 6500 computer) in FØRTRAN IV. The simplex technique is used in the solution algorithm. With only minor changes in the read and write statements, the program can be used on any system with a FØRTRAN IV compiler. As currently dimensioned, the following constraints on problem size must be observed:

$$N_S + N_R \leq 45$$

$$N_S \leq 30$$

$$N_C \leq 3$$

$$N_S[N_S + N_R + 3(N_C) + 20] \leq 4000$$

where

N_S = number of sources

N_R = number of receptors

N_C = number of straight line segments used to represent the cost function.

The array sizes are easily changed to handle larger problems, if desired, i.e., problem size is limited only by available storage capacity.

As previously stated, the model formulation is compatible with analysis of tactical, short-term control measures, as well as strategic, long-term control. In the former situation, the source-receptor transfer functions, f_{ijk} (E_{ij}), are replaced by the functions applicable to the short-term control measures being considered. The normal long-term cost functions are replaced with incremental costs of short-term control measures available for each source. The constraints, S_j, are replaced by a set of g.l.c.'s, which represent the upper limit tolerable in an acute situation. The model, as formulated, then computes a minimum-cost set of control measures for this situation.

2.2.2 Setting Up the Diffusion Model

The diffusion model receptor net constructed for this study consists of a widely dispersed grid of 49 receptors spaced at 15 kilometer intervals covering the entire area, and 136 additional receptors at closer intervals covering the more industrialized portions of the area. Figure 2-3 shows the receptor net.

Parameters input to the model are:

	SO_2	Particulates
• Ambient pressure, millibars	997.29	997.29
• Ambient temperature, °Kelvin	285.5	285.5
• Mixing height, meters	1387.0	1387.0
• Half life, hours	3.0	Infinite

The model was calibrated using 1968 data from 23 SO_2 and 15 particulate measuring stations. Regression parameters were as follows:

	SO_2	Particulates
• y-intercept, $\mu g/m^3$	36.97	62.11
• slope	.2711	.6039
• regression coefficient	.692	.623
• regression coefficient of 5% confidence level	.413	.514

The particulate y-intercept is considerably higher than is normally encountered and calls into question the accuracy of the absolute value of the particulate air quality results obtained. The air quality conclusions drawn from diffusion model results should not be seriously affected by this high y-intercept value since they are comparative in nature.

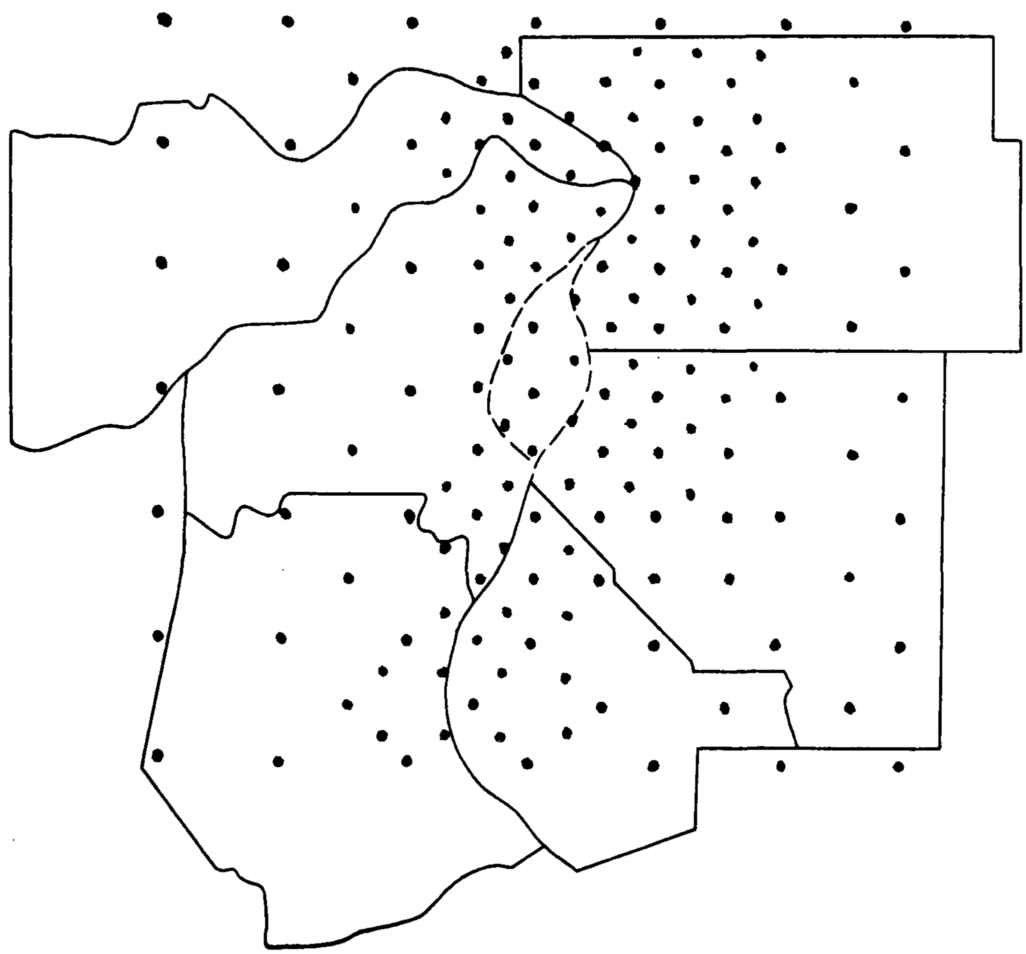


Figure 2-3. Diffusion Model Receptor Grid

2.2.3 The Three Strategies

2.2.3.1 Conventional Source Category Strategy

The emission standards used in the Source Category Strategy are as follows:

- Particulate Fuel Combustion

  HEAT INPUT STANDARD

  Figure 2-4 is used to define a design allowable emission rate, pounds per 10^6 BTU. The actual allowable emission rate reflects actual source operating practice as follows:

  $$\text{Allowable Emission Rate} = (\text{Design Allowable Emission Rate}) * \frac{\text{Actual Heat Input, BTU/Hr}}{\text{Rated Capacity, BTU/Hr}}$$

- Particulate Industrial Process

  PROCESS WEIGHT STANDARD

  Figure 2-5 is used to define a design allowable emission rate, pounds per hour, based on maximum process weight. This value is divided by the "use factor," which is the ratio of maximum to actual process weight. In reality, the use factor in this analysis was uniformly considered to be 1.0 due to lack of data, and process weight entered was therefore "average" process weight.

- Particulate Solid Waste Disposal

  POTENTIAL EMISSIONS STANDARD

  Figure 2-6 defines the design allowable emission rate based on the uncontrolled (potential) emission rate for each source operating at maximum capacity. This rate is calculated as:

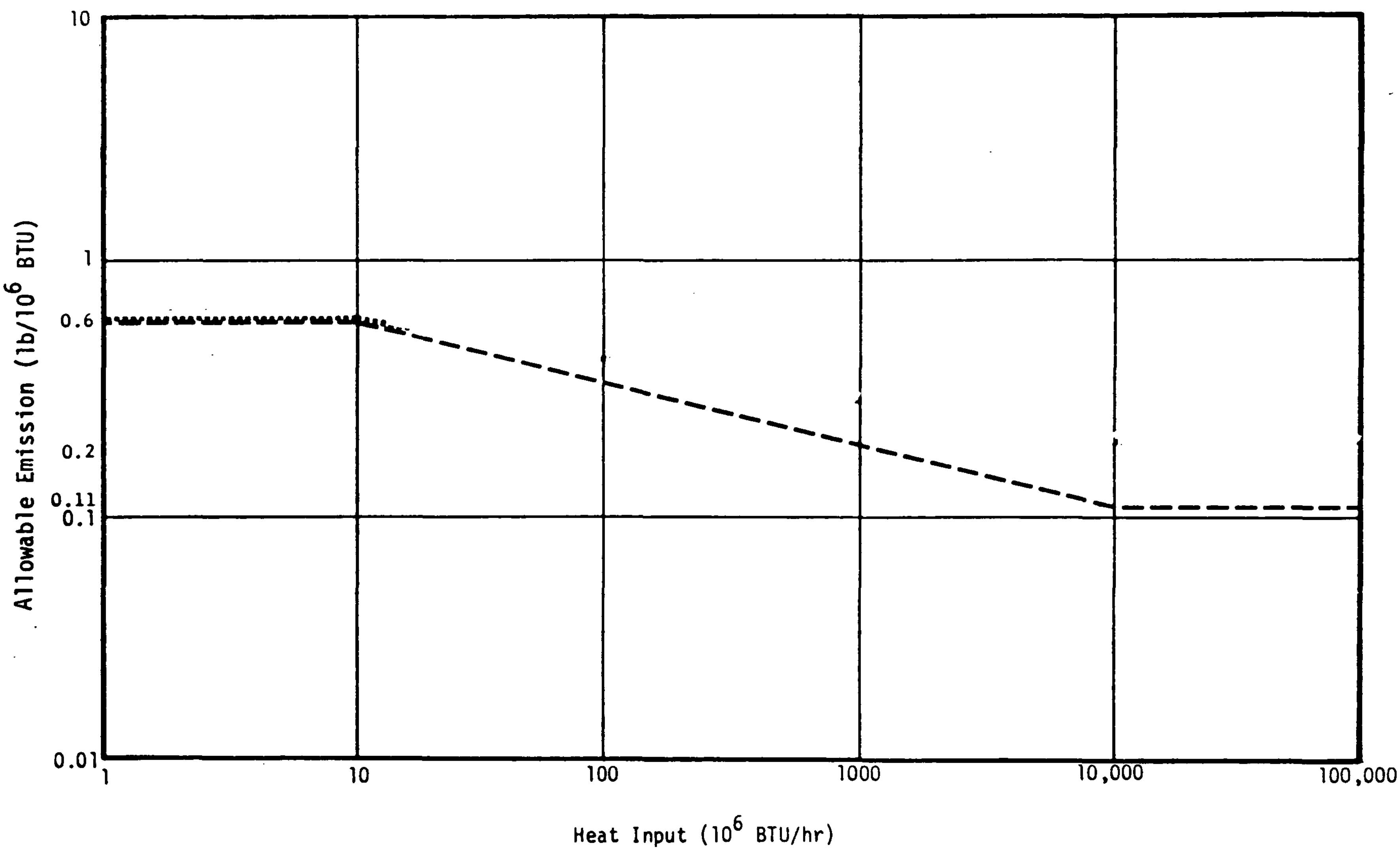


Figure 2-4 Allowable Particulate Emissions Based on Input Heat Capacity

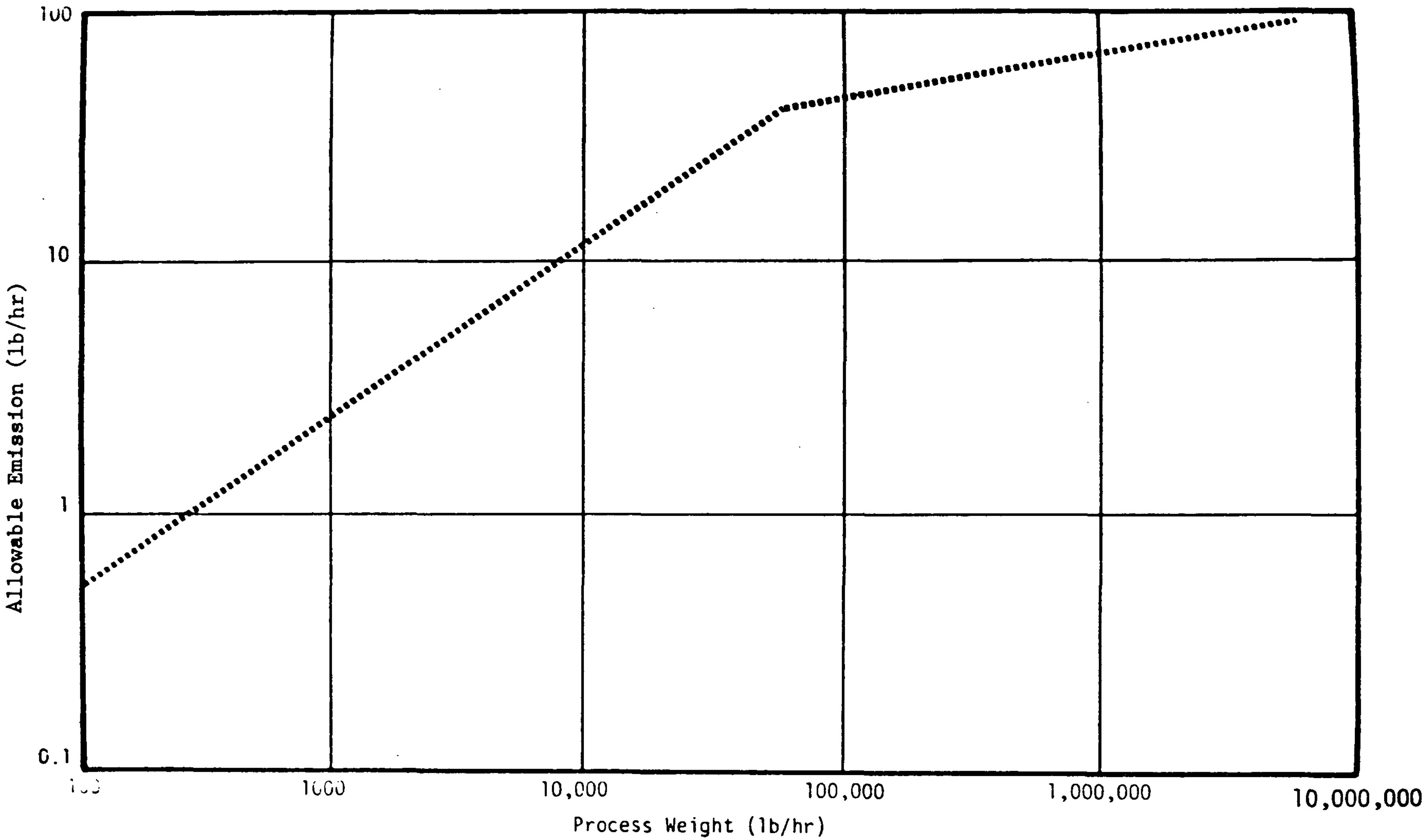


Figure 2-5. Allowable Particulate Emissions Based on Industrial Process Weight

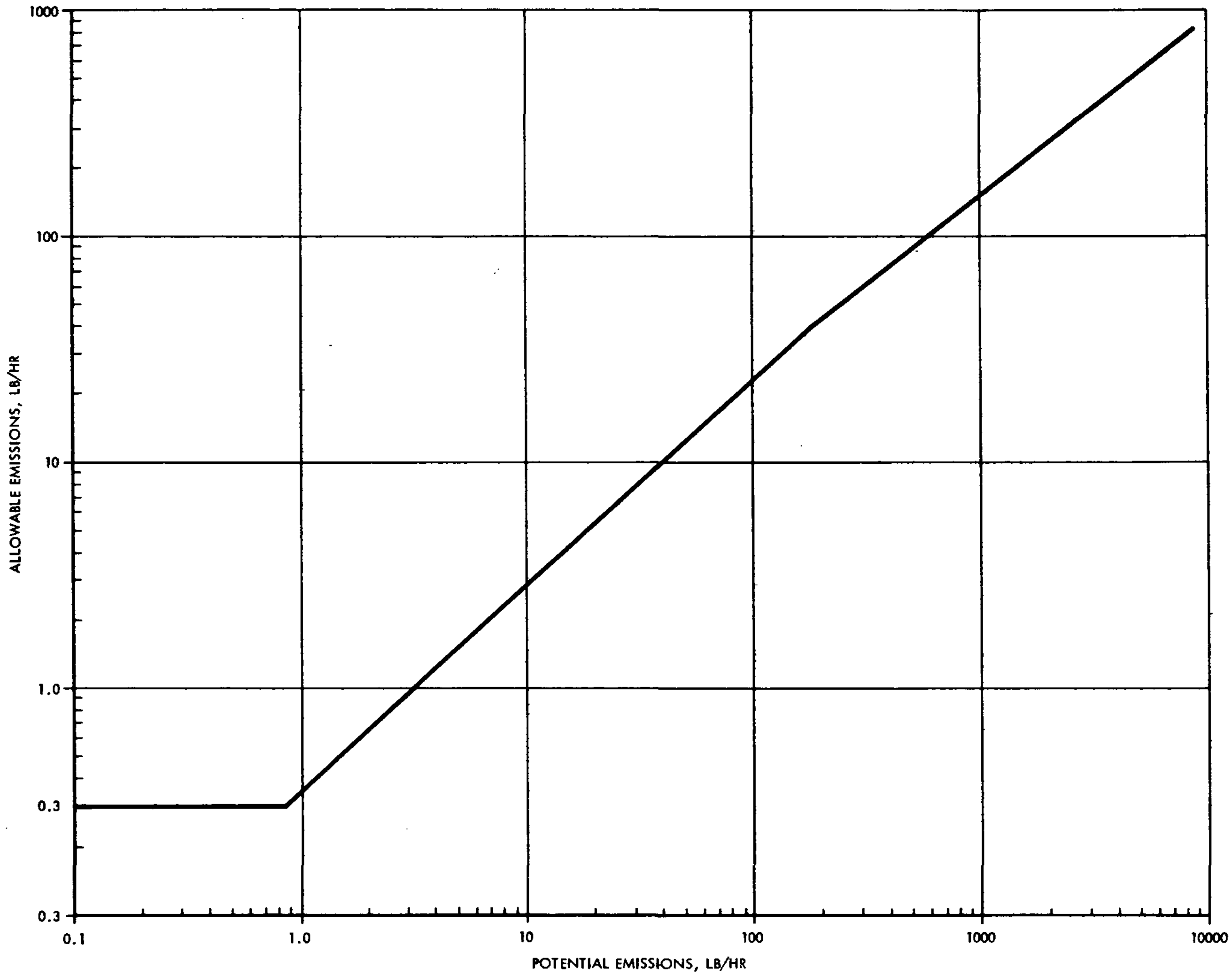


Figure 2-6. Potential Emissions Standard

$$\frac{(\text{Existing Emission Rate})\ (\text{Use Factor})}{1 - \text{Existing Control Efficiency}}$$

- SO_2 Fuel Combustion

  EQUIVALENT FUEL SULFUR CONTENT RESTRICTION:
  1% SULFUR COAL, 1.38% SULFUR OIL

  This standard applies a restriction on the sulfur level of fuels used, or else demands an equivalent reduction in SO_2 emissions via flue gas desulfurization techniques.

- SO_2 Industrial Process

  EXHAUST CONCENTRATION STANDARD:
  500 PARTS PER MILLION

Area source emissions were appropriately scaled by constructing Table 2-2 from emission and fuel consumption data, and then applying the emission standards to scale down appropriate segments of the total emissions (percent reductions were calculated by using average values for existing fuel sulfur and ash levels and BTU contents). Scale factors calculated for this strategy were:

- SO_2 - .53
- Particulates - .60

Table 2-2 . Breakdown of Area Source Emissions, St. Louis AQCR

Category	SO_2		Particulates	
	Tons/Year	Percent of Total	Tons/Year	Percent of Total
Transportation	7272	29	8784	52
Residential	12425	50	3041	18
Commercial/ Institutional	4720	19	1540	9
Refuse Disposal	716	3	3456	21
• Incinerators	500	2	0	0
• Open Burning	216	1	3456	21

2.2.3.2 Rollback Strategy

As discussed in Section 2.1.2, the application of a Rollback Strategy requires a knowledge of existing air quality and a definition of an air quality standard. Under normal circumstances, the maximum concentration in the Rollback reduction formula is a measured value, since Rollback is used primarily in the absence of diffusion modeling. However, this study attempts to maintain strict consistency between the three strategy types by keeping all input data within the same model framework. Thus,

THE "MAXIMUM CONCENTRATION" USED IN THE ROLLBACK EQUATION IS DEFINED AS THE HIGHEST COMPUTED VALUE OF EXISTING GROUND LEVEL CONCENTRATION FOUND IN THE DIFFUSION MODEL RECEPTOR SYSTEM.

For this study, these values are:

- SO_2 - 144 $\mu g/m^3$
- Particulates - 171 $\mu g/m^3$

} Maximum concentrations

Also, the air quality standard used for both Rollback and Least Cost Strategies will be that attained by the Conventional Source Category Strategy, thus allowing a strict comparison to be made between the three. These standards are:

- SO_2 - 64 $\mu g/m^3$
- Particulates - 96 $\mu g/m^3$

} Air Quality Standards

Finally, background concentration levels are as follows:

- SO_2 - 37 $\mu g/m^3$
- Particulates - 62 $\mu g/m^3$

} Background concentrations

Applying these values to the Rollback equation, one finds that:

• $R (SO_2)$	= .75
• R (particulates)	= .69

In other words, total regional SO_2 emissions must be cut by 75 percent, and particulate emissions by 69 percent.

According to Table 2-2, 52 percent of particulate area source emissions are caused by transportation vehicles, which cannot be controlled by "stationary source" emission standards. Thus, 69 percent control of particulate area source emissions is not possible using such standards. Using the same set of emission standards on both point and area sources, a 69 percent reduction in <u>total</u> regional emissions is attained by applying standards of sufficient stringency to attain a 77 percent reduction in point source particulate emissions; the same standards will achieve an approximately 40 percent reduction in area source emissions (which comprise slightly more than 20 percent of total regional particulate emissions). Thus, a 75 percent reduction in SO_2 and a 77 percent reduction in particulate point source emissions is required because of the inability to control a portion of the area source emissions.

As discussed in Section 2.1.2, the strategy selected to accomplish this reduction consists of potential emission, heat input and equivalent sulfur content standards. For the sake of simplicity and ease of calculation, the potential emissions curves selected are straight lines passing through the origin (compare to Figure 2-6) and the heat input curve is a straight line parallel to the "heat input" axis (compare to Figure 2-4)... in other words, the curves are specified by constant values of (allowable emissions, lb/hr/potential emissions, lb/hr) and (allowable emissions, lb/heat input, 10^6 BTU). A sample derivation of an emission standard is as follows:

Particulate fuel combustion standard: heat input standard

Total heat input = 5.5321×10^{10} BTU/hr.

Existing emissions = 27290 pounds/hr.

Emissions after 75 percent reduction = 6822 pounds/hr.

$$\text{Emissions standard} = \frac{6822 \text{ pounds/hr allowable emission}}{5.5321*10^{10} \text{ BTU/hr heat input}}$$

$$= \frac{.123 \text{ pounds allowable emissions}}{10^6 \text{ BTU}} =$$

Following this procedure for all of the emission standards results in a Rollback Strategy as follows:

- Particulate fuel combustion sources........ - .123 pounds/10^6 BTU
- Particulate industrial process sources........... - $.117 \left(\frac{\text{Allowable emissions,lb/hr}}{\text{Potential emissions,lb/hr}}\right)$
- Particulate solid waste disposal sources.......... - $.117 \left(\frac{\text{Allowable emissions,lb/hr}}{\text{Potential emissions,lb/hr}}\right)$
- SO_2 fuel combustion sources - .8% sulfur coal or equivalent
- SO_2 industrial process sources.................. - $.25 \left(\frac{\text{Allowable emissions,lb/hr}}{\text{Potential emissions,lb/hr}}\right)$

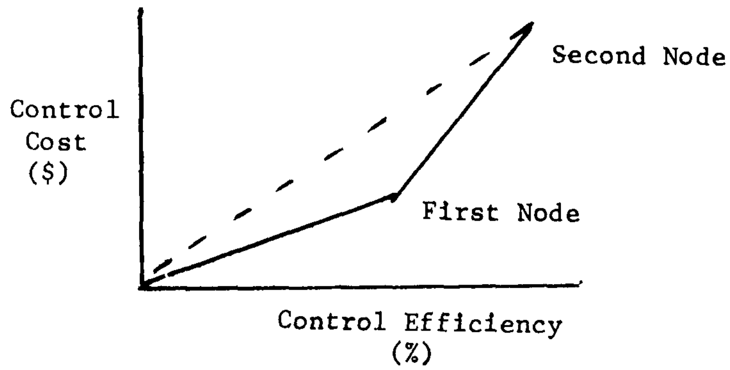
Each emission standard is designed to control 77 percent (first three standards) or 75 percent (last two) of emissions in its category. Because it is difficult to calculate exactly how effective (in terms of emission reductions) each standard will be, a second particulate strategy with less severe standards was also run. However, the first strategy was very successful, yielding a total emission reduction of 69 percent.

Table 2-3. Input Data for Sources Controlled Under the Least-Cost Strategy

Source No.	Standard Industrial Classification	Site No.	Existing Emission Rate(T/D)	Control Cost Data: First Node Cost, $/Ton	First Node Emission Reduction	Second Node Cost, $/Ton	Second Node Emission Reduction
1	2011; Meat Packing, Boiler	001	6.25	16.	75.	30.	99.
2	2041; Feed and Grain Mill	001	5.70	16.	80.	24.	99.
3	2041; Feed and Grain Mill	009	11.37	11.	75.	53.	99.
4	2041; Feed and Grain Mill	010	17.15	15.	75.	79.	99.
5	2041; Feed and Grain Mill	012	5.09	341.	52.	1048.	99.
6	2046; Wet Corn Milling, Boiler	001	4.21	19.	75.	38.	99.
7	2082; Brewery, Boiler	001	2.95	13.	75.	20.	99.
8	2082; Brewery, Boiler	002	2.67	600.	76.	929.	97.1
9	2600; Paper Products, Boiler	002	21.22	4.	75.	8.	99.
10	2800; Chemical PH., Boiler	002	3.42	34.	75.	310.	99.
11	2816; Inorg. Pigments, Boiler	002	7.30	63.	52.	71.	99.
12	2819; Inorg. Ind. Chem Plant	003	6.00	32.	68.	57.	99.
13	2819; Inorg. Ind. Chem Plt., Boiler	007	10.70	4.	75.	11.	99.
14	2911; Petro. Refinery	001	6.00	128.	75.	355.	99.
15	2911; Petro. Refinery	002	4.72	58.	52.	65.	99.
16	2952; Asphalt Batch., Boiler	001	2.90	15.	75.	91.	99.7
17	3241; Cement Plant, Dry Process	001	3.28	2.	75.	4.	99.
18	3241; Cement Plant, Dry Process	003	3.68	118.	97.	125.	99.
19	4911; Powerplant	001	3.72	214.	93.	270.	99.
20	4911; Powerplant	002	7.60	251.	63.	273.	99.
21	4911; Powerplant	003	5.00	86.	66.	115.	92.4
22	4911; Powerplant	004	5.10	909.	74.	1353.	99.
23	4911; Powerplant	005	11.90	75.	81.	98.	99.
24	4911; Powerplant	006	80.00	5.	75.	8.	89.2
25	4911; Powerplant	008	6.90	104.	75.	799.	99.
26	4911; Powerplant	009	32.50	39.	75.	53.	99.
27	4911; Powerplant	010	5.60	240.	93.	305.	99.

2.2.3.3 Least-Cost Control Strategy

In Table 2-3, input data for the 27 major point sources of particulates which were controlled under the least-cost strategy are described. Emissions from the remaining point sources and all area sources were allowed to remain at the existing levels. The first column gives the source number which is listed here for convenience in later reference. The second column is an indication of the type of point source being controlled, and both the Standard Industrial Classification code (SIC) and the descriptive name of the point sources are given. The site number in column three allows the entries in this table to be correlated with those in the St. Louis emission inventory which has been used throughout the studies described in this report. The existing particulate emission rate (tons per day) is given in the fourth column; all point sources over 2.5 tons per day were selected from the basic St. Louis emission inventory. It is interesting to note that these 27 sources contribute 79% of the total particulate emissions from point sources in the region. The last four columns in this figure represent data taken from the IPP Control Cost Model. The data defines two of the three "nodes" (end points) of the piecewise linear curves of control efficiency versus annual cost; the third "node" is the origin. The sketch below shows a representative curve.



The emission reduction at the second node represents the maximum possible emission reduction at that particular source, given the state-of-the-art of control technology. This data was obtained by examining the IPP Control Cost Model output, plotting points on the cost versus control efficiency curve for each of the applicable control devices, and then drawing that two-segment piece-wise linear curve which best represented a lower envelope for these points.

The receptors selected for use in the Least-Cost Model (Figure 2-7) are a subset of those used for the rollback and conventional source category strategies. This was done so that the source contribution tape written by the diffusion model could be used for all three strategies. The air quality standard achieved in the conventional strategy, i.e., the maximum ground level concentration at any receptor in the region, was 96 micrograms per cubic meter. The maximum for the nine receptors selected for use in the Least-Cost Model was 85 micrograms per cubic meter, i.e., none of the nine receptors used here reached the 96 $\mu g/m^3$ maximum for the region. To achieve results which would allow a direct comparison between the least-cost and the conventional approaches, the linear programming algorithm used in the Least-Cost Model was constrained to achieve the same air quality as was achieved by the conventional source category over this set of nine receptors i.e., the 85 microgram level.

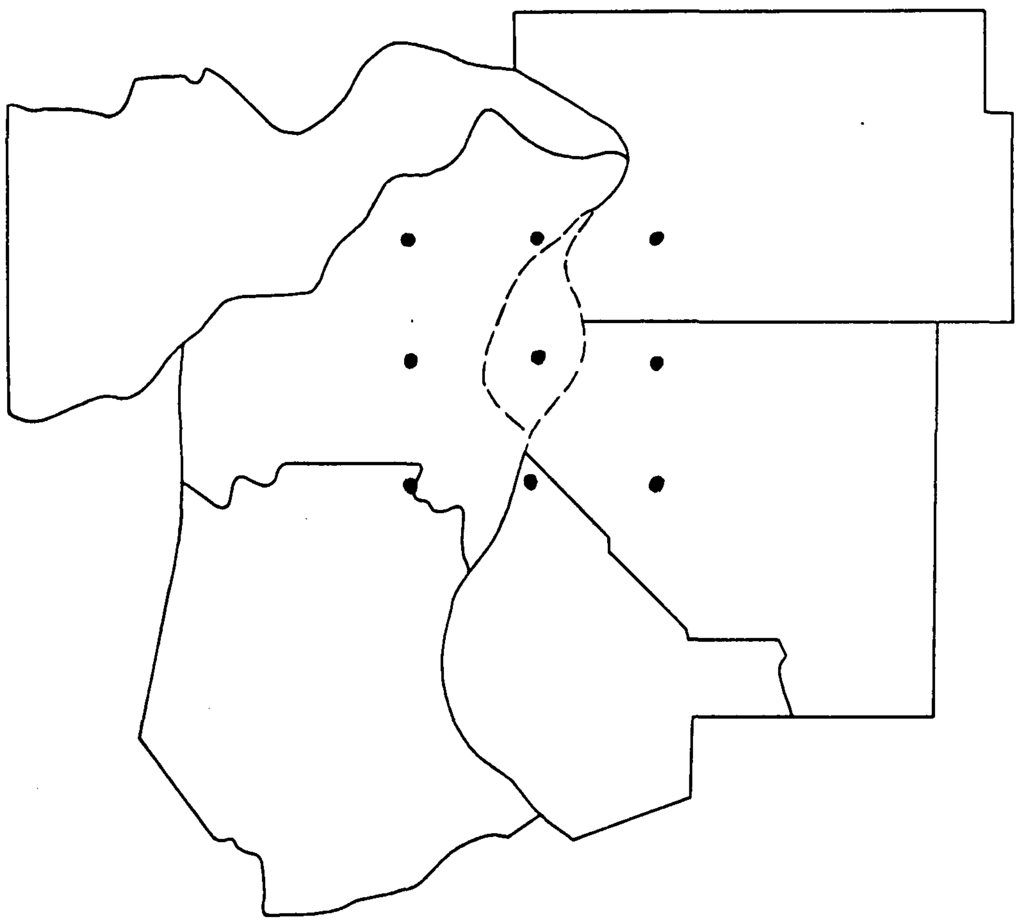


Figure 2-7. Receptor Locations For The Least-Cost Model

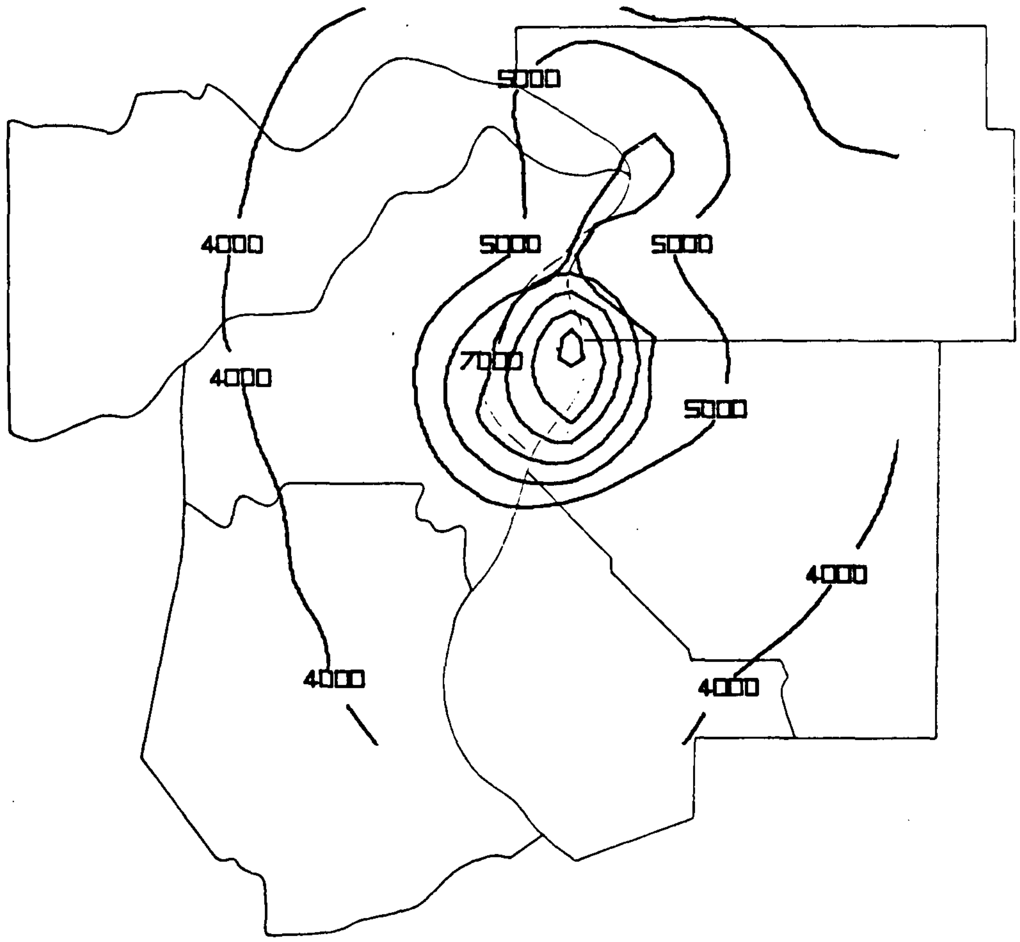
2.3 RESULTS

2.3.1 The St. Louis AQCR Today

According to the emission source inventory used in this study, the St. Louis AQCR has total emissions of 465.9 Tons/Day of particulates and 1685.4 Tons/Day of SO_2. Table 2-4 illustrates the breakdown of point and area source emissions. Present air quality, as noted in Section 2.2.3.2, is 144 $\mu g/m^3$ of SO_2 and 171 $\mu g/m^3$ of particulates at the worst receptor (as computed by the diffusion model). According to the plots of ground level concentrations (isopleths) in Figures 2-8 and 2-9, however, the level of particulate air quality, on the average, is far worse than that of SO_2 ... in the core area, particulate ground level concentration is an average of about 40 to 50 $\mu g/m^3$ higher than the SO_2 concentration.

Table 2-4. St. Louis AQCR - Existing Conditions

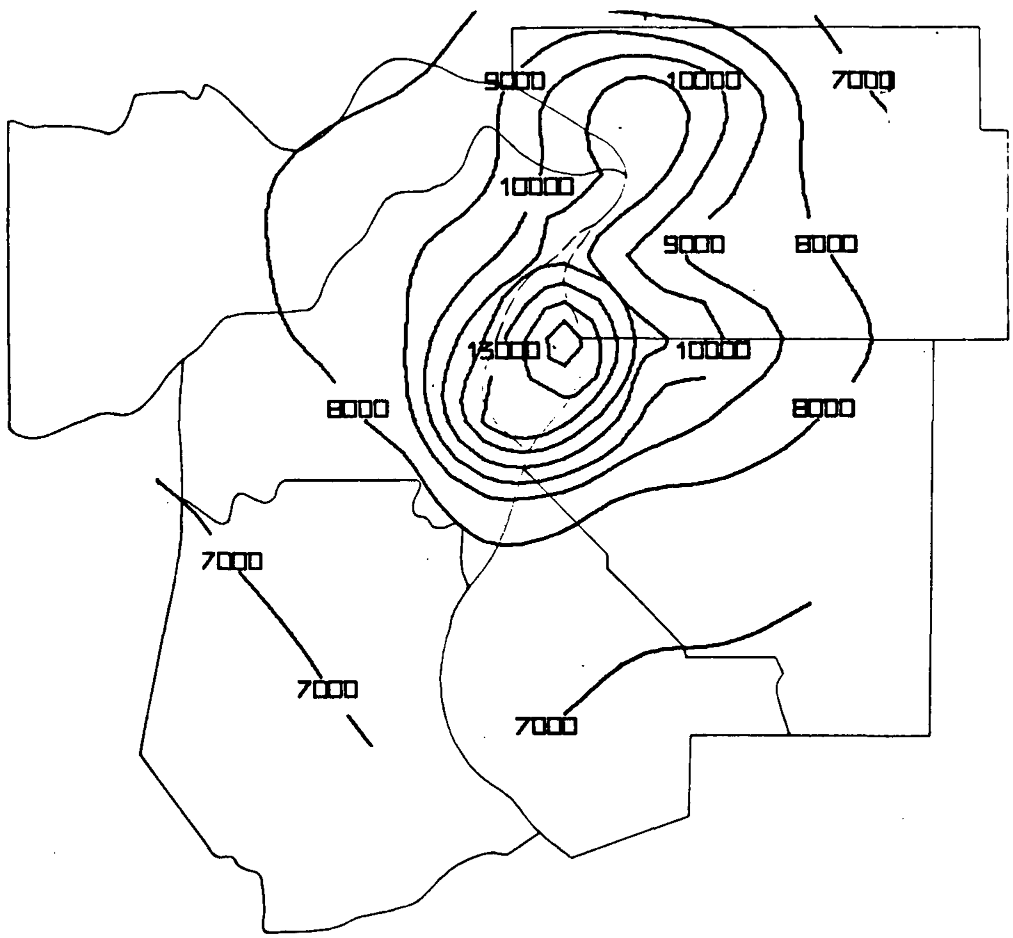
	SO_2	Particulates
• Existing Point Source Emissions	1639.2	358.8 Tons/Day
• Existing Area Source Emissions	46.2	107.1 Tons/Day
• Total Existing Emissions	1685.4	465.9 Tons/Day
• Air Quality (Highest Concentration)	144.2	170.6 $\mu g/m^3$
• Average Concentration At 20 Highest Receptors	85.9	138.2 $\mu g/m^3$



$SO_2 \sim \frac{1}{100}\ \mu g/m^3$

Figure 2-8.

St. Louis AQCR Existing SO_2 Ground Level Concentrations



Particulate ~ $\frac{1}{100}$ µg/m^3

Figure 2-9.

St. Louis AQCR Existing Particulate Ground Level Concentrations

2.3.2 Conventional Source Category Strategy

The Conventional Source Category Strategy described in Section 2.2.2.1 achieves a 69 percent reduction in both SO_2 and particulate emissions. Table 2-5 illustrates the breakdown of point and area source reductions, plus other significant strategy results. Figures 2-10 and 2-11 present the isopleths for SO_2 and particulate ground level concentrations. A comparison between the pre-control and post-control isopleths indicates that emission reduction appears to be fairly uniform throughout the region, since the isopleths are fairly similar in shape ... though of course the concentration values are considerably lower in the latter two figures.

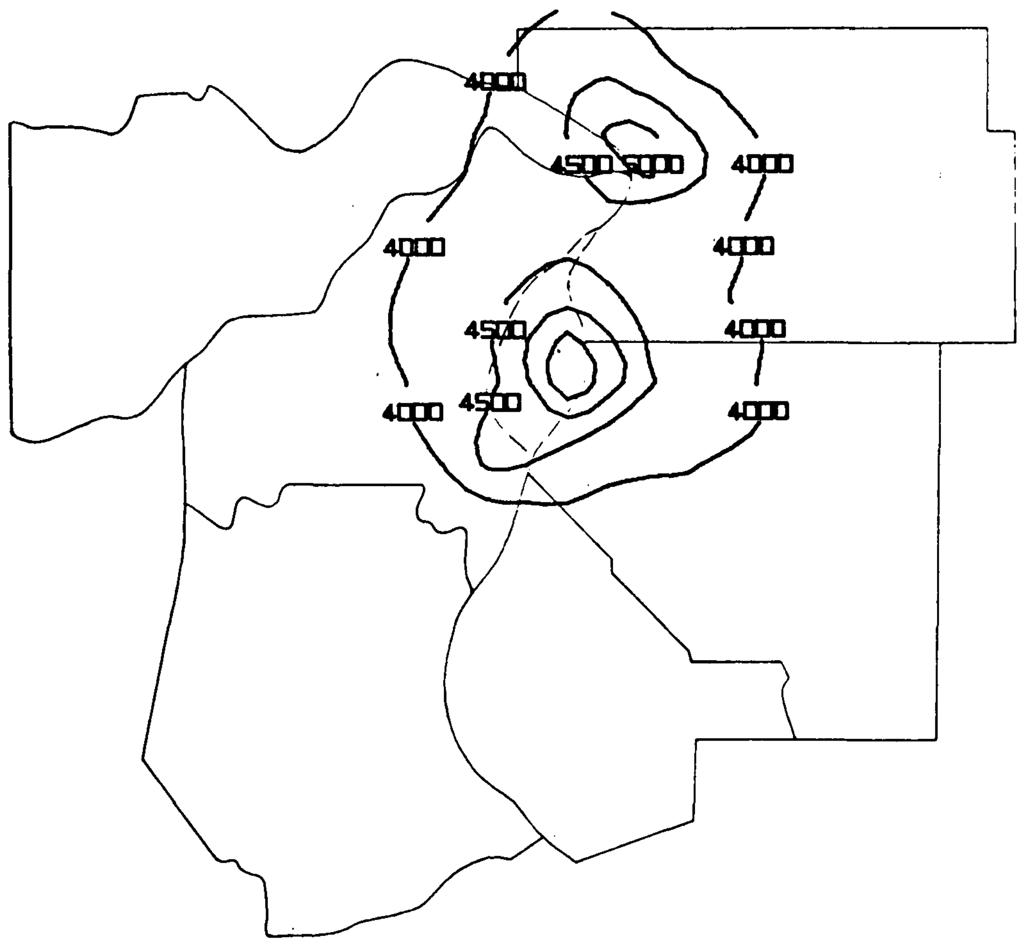
The fact that this relatively strict set of emission standards did not lower maximum particulate air quality levels to below 90 $\mu g/m^3$ should not be greeted with dismay. It should be noted that the particulate "background" of 62 $\mu g/m^3$ means that a total shutdown of every particulate emission source in the entire AQCR will lower computed air quality to 62 $\mu g/m^3$ and no lower. A background concentration level of this magnitude is almost certainly due to a poor model calibration resulting from inadequate input air quality data, especially in the "clean air" portions of the region. The discrepancy between the collection dates for the air quality and emission data - 1968 and 1970, respectively - undoubtedly plays a significant role in this probable error.

Table 2-5

St. Louis AQCR - Results of Conventional Source Category Strategy

	SO_2	Particulates
• Post-Control Point Source Emissions	501.6	81.1 Tons/Day
• Post-Control Area Source Emissions	24.5	64.2 Tons/Day
• Total Post-Control Emissions	526.1	145.3 Tons/Day
• Air Quality Achieved (Highest Concentration)	63.7	95.6 $\mu g/m^3$
• Average Concentration at 20 Highest Receptors	52.5	87.4 $\mu g/m^3$
• Average Reduction in Concentration	9.5	18.7 $\mu g/m^3$
• Total Cost of Strategy	17,949,000	$10,371,000/Year
• Cost-Effectiveness*	1,880,500	$551,500/($\mu g/m^3$)

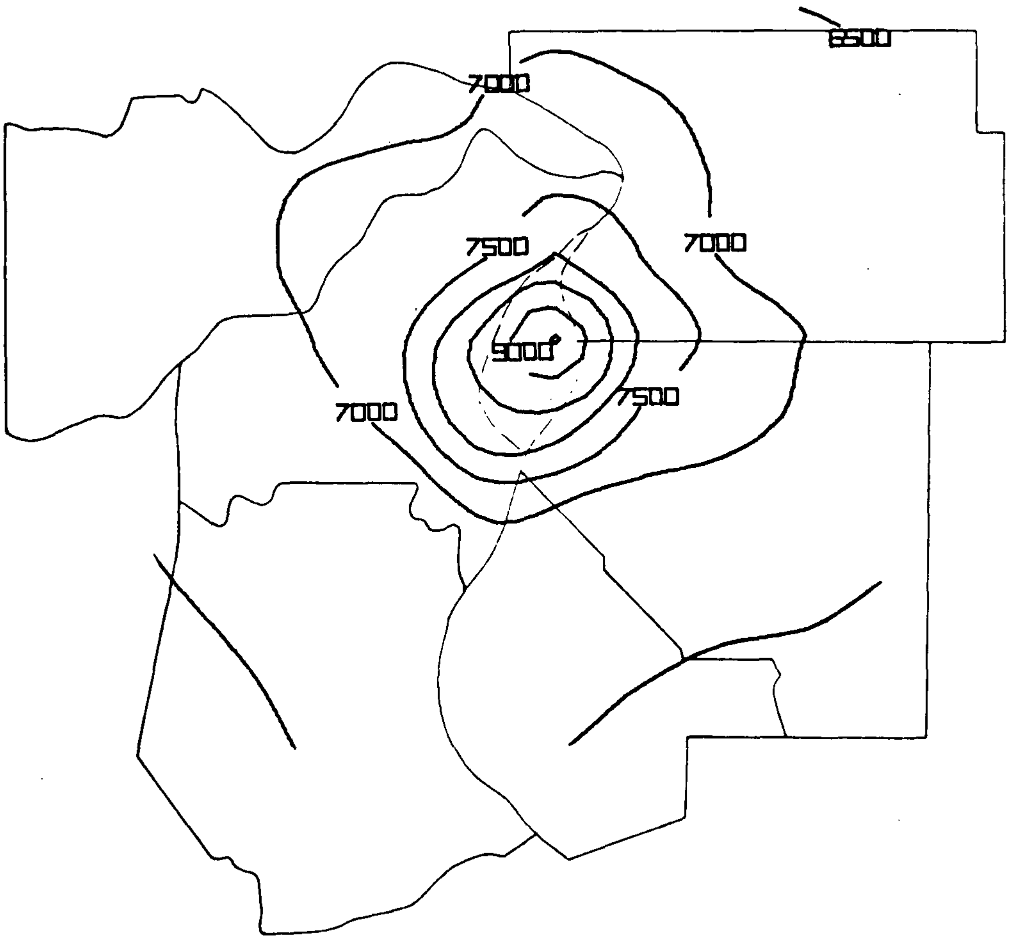
* Cost effectiveness is total cost divided by average reduction in ground level concentration.



$SO_2 \sim \frac{1}{100}$ μg/m^3

Figure 2-10.

St. Louis AQCR - SO_2 Ground Level Concentrations After Imposition Of Conventional Source Category Strategy



Particulate ~ $\frac{1}{100}$ μg/m^3

Figure 2-11.

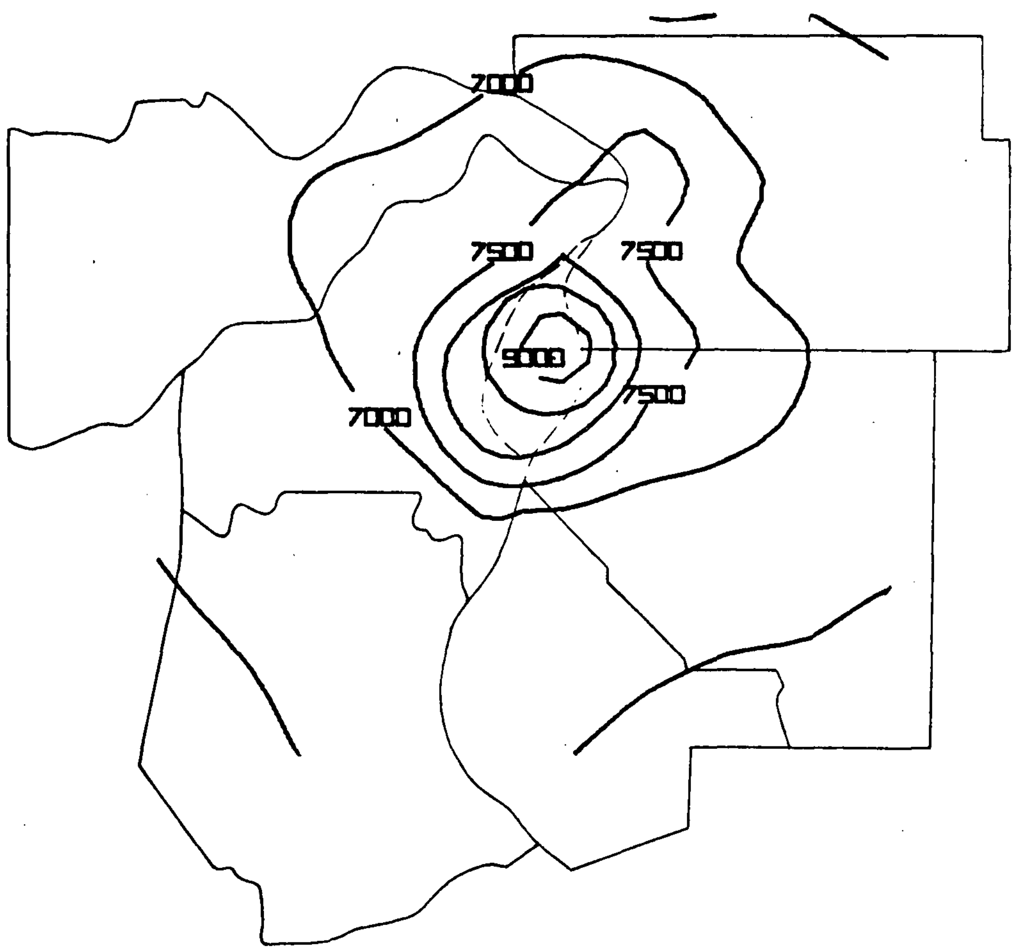
St. Louis AQCR - Particulate Ground Level Concentrations After Imposition of Conventional Source Category Strategy

2.3.3 Rollback

The Rollback Strategies defined in Section 2.2.3.2 achieve a 74 percent reduction in SO_2 emissions and a 69 percent reduction in particulate emissions. Table 2-6 illustrates the breakdown of point and area source emission reductions, air quality achieved, and other strategy results. Figures 2-12 and 2-13 present the isopleths for SO_2 and particulate ground level concentrations. The Rollback and Conventional Source Category isopleths are very similar, although the Rollback SO_2 strategy shows greater reductions in concentration levels.

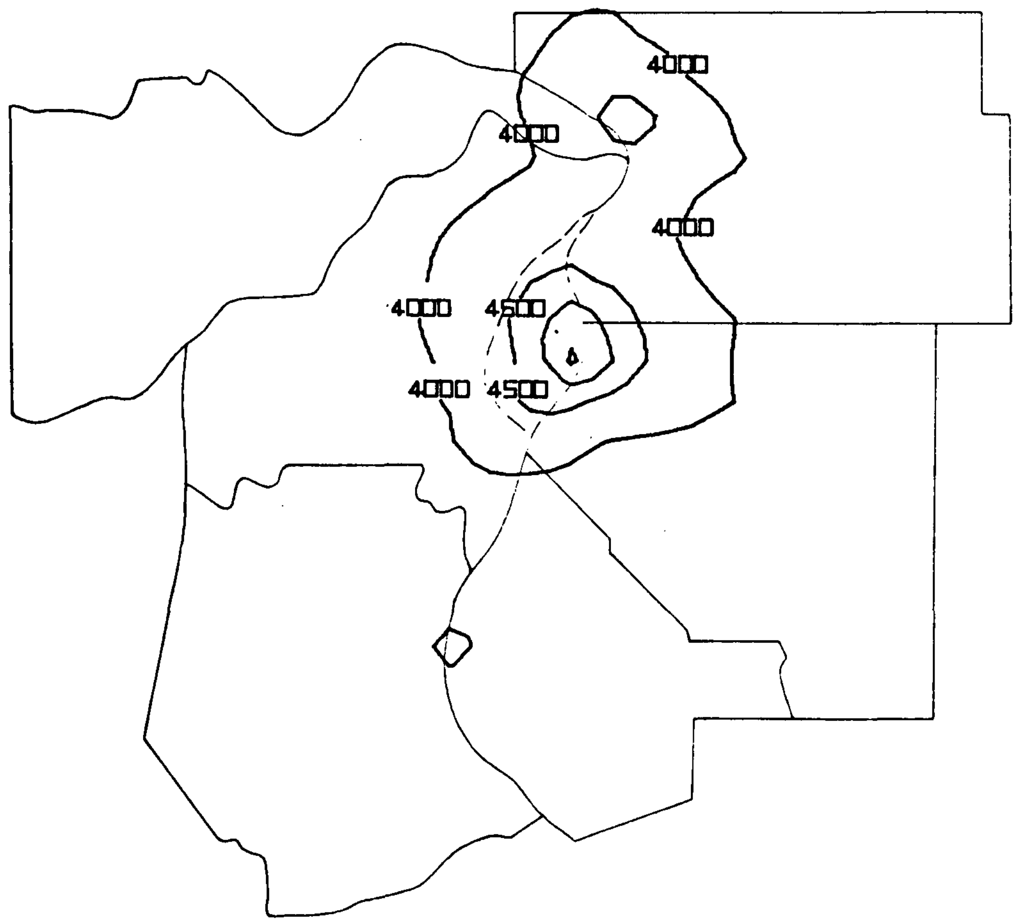
Table 2-6. St. Louis AQCR - Results of Rollback Strategy

	SO_2	Particulates
• Post-control point source emissions	421.6	78.9 tons/day
• Post-control area source emissions	21.7	64.2 tons/day
• Total post-control emissions	443.3	143.1 tons/day
• Air quality achieved (highest concentration)	60.3	95.3 $\mu g/m^3$
• Average concentration at 20 highest receptors	48.9	86.2 $\mu g/m^3$
• Average reduction in concentration	10.5	18.8 $\mu g/m^3$
• Total cost of strategy	28,462,000	\$9,551,000/year
• Cost-effectiveness	2,704,200	\$ 509,200/($\mu g/m^3$)



Particulates ~ $\frac{1}{100}$ μg/m^3

Figure 2-12. St. Louis AQCR Particulate Ground Level Concentrations After Imposition of Rollback Strategy



$SO_2 \sim \frac{1}{100}$ μg/m^3

Figure 2-13. St. Louis AQCR - SO_2 Ground Level Concentrations After Imposition of Rollback Strategy

2.3.4 Cost/Benefit Comparison of Rollback and Conventional Strategies

Figures 2-14 and 2-15 depict the costs and benefits of the Rollback and Conventional Source Category Strategies for SO_2 and particulates, respectively. The optimum air quality, that point where marginal costs are equal to marginal benefits, is at the 48 $\mu g/m^3$ air quality level (where "air quality" is weighted with respect to population). For SO_2, the actual weighted air qualities achieved by the SO_2 strategies are:

Existing	65.2 $\mu g/m^3$
Rollback	44.1 $\mu g/m^3$
Conventional	45.9 $\mu g/m^3$

The particulate cost curve is drawn somewhat arbitrarily, because two of the three data points were almost on top of each other. The shape of the curve was determined by assuming an asymptote at the 62 $\mu g/m^3$ particulate background. The optimum air quality is at approximately 82 $\mu g/m^3$. The weighted air qualities achieved by the strategies are:

Existing	112.01 $\mu g/m^3$
Rollback	78.47 $\mu g/m^3$
Conventional	78.99 $\mu g/m^3$

2.3.5 Least-Cost Control Strategy

Table 2-7 presents the effects of the Least-Cost Strategy on the 27 major particulate point sources. The source numbers correspond to those in Table 2-3. Most of the 27 sources are controlled to the maximum extent; those sources which are not have been marked with an asterisk. A comparison with Table 2-5 reveals that the least-cost approach achieves an emission reduction which is 27 tons/day less than that of the conventional approach (81 tons reduction for least-cost versus 108 tons reduction for conventional).

Thus, the least-cost approach is able to achieve the same air quality standard as the conventional approach while allowing total emissions to be 25 percent greater. The total regional cost of the least-cost strategy is 6 million dollars, which is a little more than half that incurred in applying the conventional strategy.

The air quality impact of the least-cost strategy is shown in Table 2-8. Ground level concentrations for the least-cost and conventional strategies are compared at each of the nine receptors. An indication of the cost which would be incurred in lowering the air quality standard is given by the marginal cost presented in column four. Since only two of the receptors have air quality which is equal to the existing standard, they are the only receptors for which cost would be incurred to lower the standard. The largest marginal cost would be incurred at receptor number 5 where an expenditure of 2.8 million dollars would be required for a 1 $\mu g/m^3$ reduction in the air quality standard.

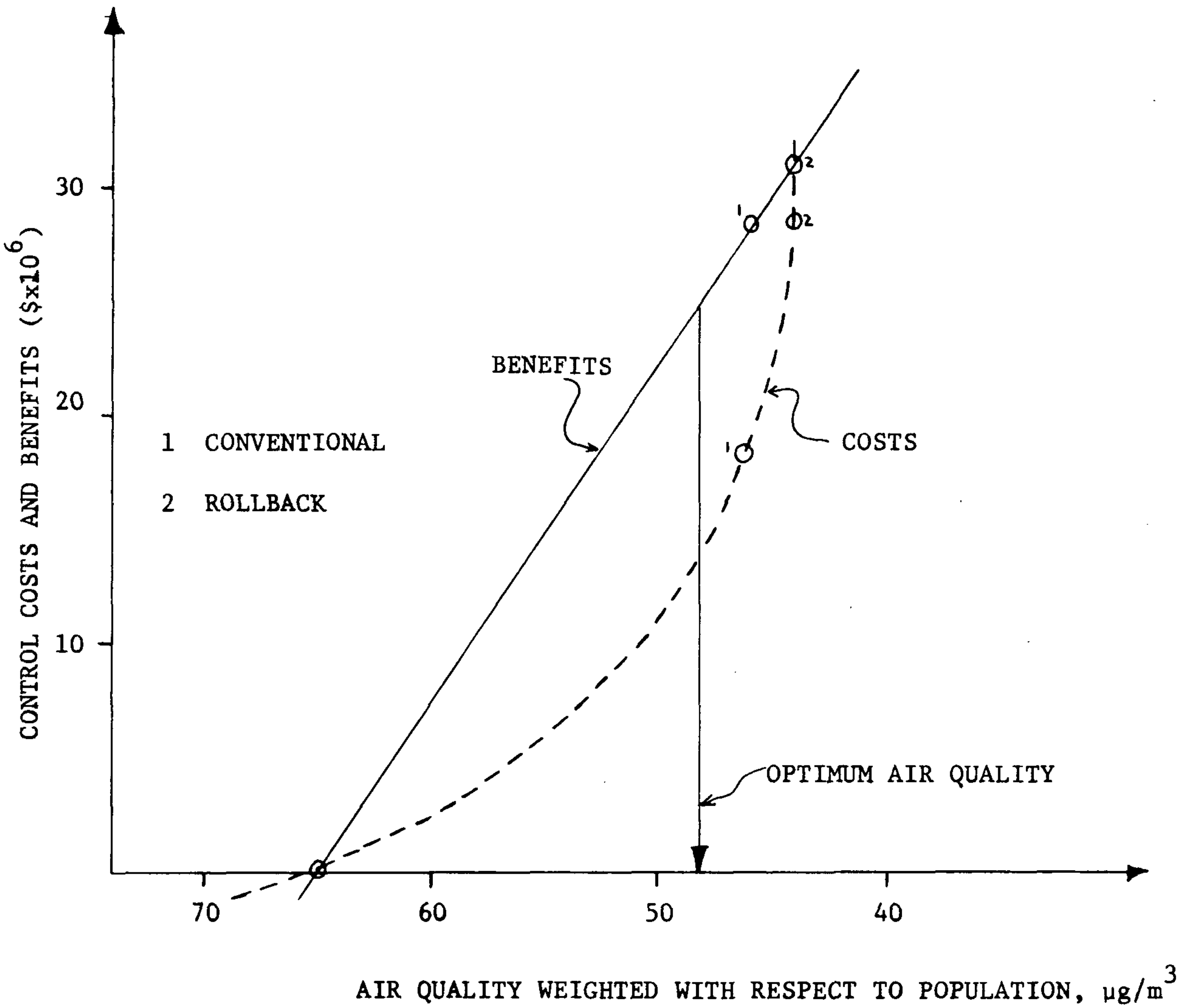


Figure 2-14. SO_2 Cost and Benefit Curves.

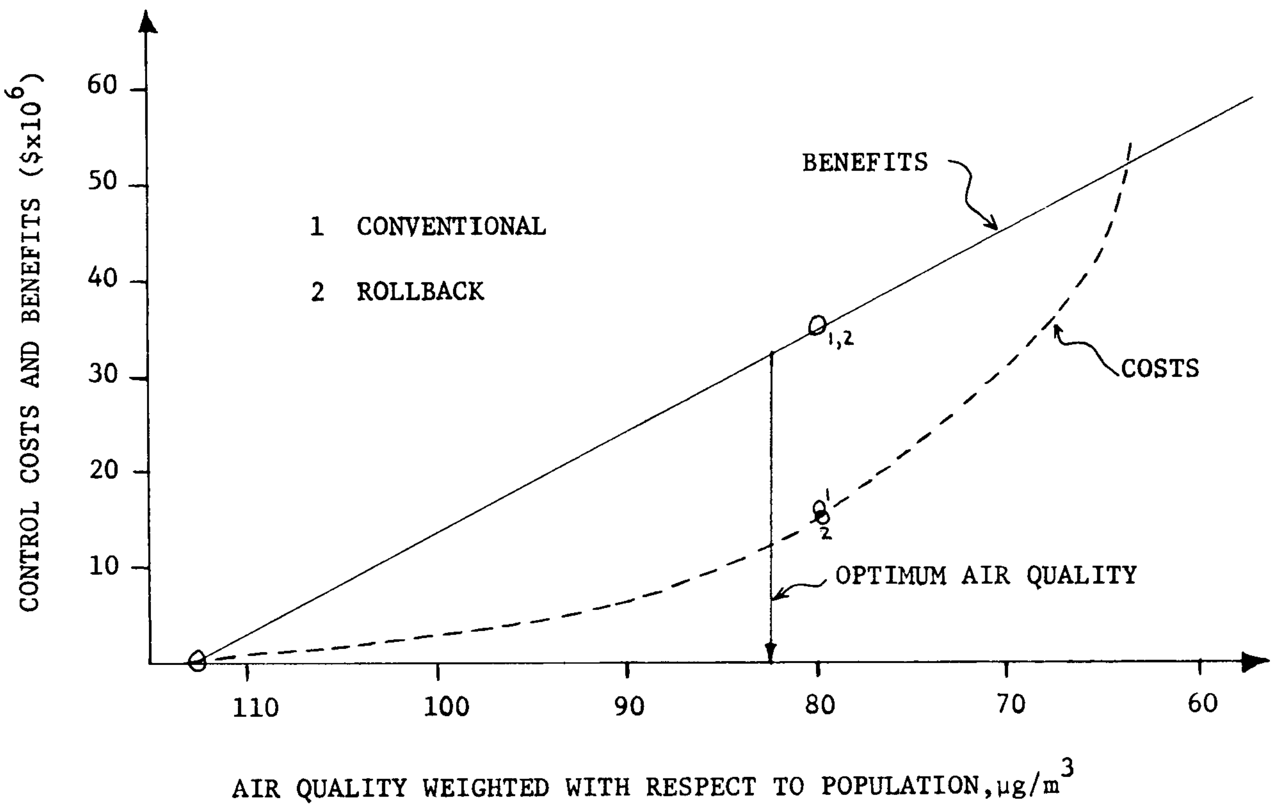


Figure 2-15. Particulate Cost and Benefit Curve.

Table 2-7. Least-Cost Strategy Impact on Controlled Particulate Sources

	Source No.	Existing Emission Rate(T/D)	Controlled Emission Rate(T/D)	Control Level	Annual Cost($x10^6)	Rate($/T)
	1	6.25	.06	99.0	.07	73.8
	2	5.70	.06	99.0	.05	57.7
	3	11.37	.11	99.0	.22	184.2
	4	17.15	.17	99.0	.49	279.0
	5*	5.09	2.83	44.5	.28	341.0
	6	4.21	.04	99.0	.06	97.4
	7	2.95	.03	99.0	.01	41.9
	8	2.67	.08	97.1	.88	2114.0
	9	21.22	.21	99.0	.06	20.5
	10	3.42	.03	99.0	.38	1172.5
	11	7.30	.07	99.0	.19	79.8
	12	6.00	.06	99.0	.12	111.8
	13	10.70	.11	99.0	.04	32.9
	14*	6.00	1.50	75.0	.21	1064.4
	15	4.72	.05	99.0	.11	72.7
	16	2.90	.01	99.7	.10	321.8
	17	3.28	.03	99.0	.01	10.2
	18*	3.68	3.68	0.	0.	118.0
	19*	3.72	3.72	0.	0.	214.0
	20*	7.60	7.60	0.	0.	251.0
	21	5.00	.05	99.0	.21	173.0
Power-	22*	5.10	1.54	69.7	1.18	909.0
plants	23*	11.90	2.26	81.0	.26	201.5
	24	80.00	.80	99.0	.23	17.4
	25*	6.90	1.73	75.0	.20	4469.8
	26	32.50	.32	99.0	.62	96.7
	27*	5.60	5.60	0.	0.	240.0
		282.93	32.75	Total Regional Cost	5.99	

Table 2-8. Least-Cost Strategy Impact on Air Quality

Receptor Number	Ground Level Concentration After Least-Cost Control, $\mu g/m^3$	Ground Level Concentration After Conventional Strategy, $\mu g/m^3$	Marginal Cost To Reduce AQ Standard ($\$x10^6$)
1	69.5	67.8	0.
2	75.5	72.0	0.
3	76.6	73.4	0.
4	71.5	70.0	0.
5	85.	85.0	2.79
6	85.	77.7	.61
7	79.5	68.2	0.
8	80.	80.0	0.
9	72.9	73.0	0.

Air Quality Standard = 85 $\mu g/m^3$

2.4 CONCLUSIONS

2.4.1 Rollback Effectiveness

The discussion in Section 2.1.2 indicates that, although a Rollback control strategy is designed to meet a specific air quality standard, actually there is no guarantee beforehand that it will do so. The SO_2 and particulate Rollback strategies used in this study (defined in Section 2.2.3.2) were successful in meeting the specified emission reduction almost exactly:

SO_2: R = .75 vs. actual reduction = 74 percent

Particulates: R = .69 vs. actual reduction = 69 percent

The air quality achieved by the particulate strategy was within 1 $\mu g/m^3$ of the target; on the other hand, the SO_2 Rollback strategy overshot its target by 3 $\mu g/m^3$, a small error by diffusion modeling standards. This small additional increment of air quality improvement is purchased at an additional cost of 10.5 million dollars per year, which represents a greater than 50 percent increase over the cost of the conventional source category strategy.

Although the Rollback strategy is defined in relationship to only one concentration value in the region....the maximum value calculated at a receptor (or, in real-life practice, the maximum measured at a pollution measuring station), a true comparison of the Rollback and conventional source category strategies should include more than a comparison of the total cost and "air quality" (maximum concentration) achieved. A look at the isopleths generated by the diffusion model indicates that there is often little relationship between the "air quality" as measured at one point and the "air quality" as indicated by the contour lines extending throughout the region. A better measure of the success of a strategy might well include the average ground level concentration throughout the region or else (if attention is to be kept on the worst parts of the region from an air quality standpoint) the average concentration at some number of the "worst" receptors. If the impact of the air quality on a per capita basis is desired, the concentrations at the receptors can be weighted by the population in zones of influence around the receptors; cost/benefit results using this procedure provide yet another measure of "air quality."

Comparing the particulate strategies on these bases, the average concentration of the Rollback strategy is .1 $\mu g/m^3$ lower than that of the source category strategy, at a cost which is $820,000/year less. The average concentration at the 20 "worst" receptors is 86.2 $\mu g/m^3$ for Rollback versus 87.4 $\mu g/m^3$ for the source category strategy. The weighted (with respect to population) air qualities attained by the two strategies are nearly identical (Rollback = 78.47 $\mu g/m^3$, conventional = 78.99 $\mu g/m^3$), and are quite near the 82 $\mu g/m^3$ optimum (marginal costs equal marginal benefits; see Figure 2-15). It can be concluded from all of the above measures that the Rollback particulate strategy <u>as applied here</u> has been a remarkable success, achieving almost precistly its target air quality in a comparatively efficient manner.

Continuing in the same manner, the "area-wide average," "average at the 20 worst receptors," and "weighted (with respect to population) average" concentrations produced by the Rollback SO_2 strategy are lower than those of the conventional source category strategy by 1.0, 3.6, and 1.8 $\mu g/m^3$ respectively. Thus, the great additional cost of the Rollback SO_2 strategy is buying a small 3 to 4 $\mu g/m^3$ improvement in the core area and essentially no improvements in the suburbs. A comparison of the cost effectiveness of the two strategies bears out the impression that the Rollback strategy is considerably less efficient than the conventional source category strategy:

Rollback cost-effectiveness = $2,704,200/($\mu g/m^3$)

Source category cost-effectiveness = $1,880,000/($\mu g/m^3$)

Going back to Figure 2-14, it can be seen that the Rollback strategy is in a very unfavorable position on the cost curve; even though the strategy's weighted air quality is within 4 $\mu g/m^3$ of the optimum air quality, the steep slope of the curve ensures considerable additional cost for the small air quality improvement.

In conclusion, while the Rollback strategy investigated in this study has achieved excellent success with respect to attaining the particulate air quality standard, it has forced an expensive over-control in attempting to attain the SO_2 air quality standard.

2.4.2 Uniform Application of Emission Standards Versus Least-Cost Strategy

The conventional source category strategy represents a uniform application of emission standards which disregards an emission source's location, ignoring the relative importance of its contribution to total ground level concentrations. Thus, plants in relatively "clean" areas are controlled to the same severity as identical plants in high pollutant concentration areas. The Least-Cost Strategy discussed in Sections 2.1.3, 2.2.3.3, and 2.3.5 achieves a minimum cost of control by applying severe controls to those plants contributing the most to air quality violations, and applying more lenient controls to plants in clean air areas. The strategy was applied to particulate control only.

The cost of the Least-Cost Strategy is 6 million dollars per year, versus 10.4 million dollars per year for the conventional source category strategy. Thus, the Least-Cost strategy achieves an air quality (as measured by the 9 receptors in Figure 2-7) identical to that attained by the conventional strategy at a cost which is 42 percent less. An inspection of Table 2-8, however, indicates that the Least-Cost Strategy gives a flatter plateau of air quality than the conventional strategy gives; that is, in most cases the ground-level concentrations under the least-cost approach will be equal to or greater than those which exist after the application of the conventional strategy. Thus, it may be expected that the "benefits" as measured by a cost/benefit model will be greatest for the conventional strategy; it remains to be seen whether the additional benefits outweigh the lesser cost of the Least-Cost strategy.

2.5 RECOMMENDATIONS

2.5.1 Rollback and Air Quality

The dependence of "air quality" on the concentration measured at a single* maximum receptor ignores the extreme sensitivity of ground level pollutant concentration measurements to small variations in receptor or

* I.e., if a region has 5 receptors measuring 64, 72, 41, 110, and 79 $\mu g/m^3$, the region is said to satisfy an air quality standard of 110 $\mu g/m^3$.

measuring station location. The differences in maximum concentration levels detected (see Section 3.3.3) in the diffusion models run - for the control strategy comparison in this section and the land use model in the following one - emphasizes the fact that altering the diffusion model receptor grid can seriously alter the maximum concentration detected while leaving the isopleth patterns relatively unchanged.

Although the overall air quality of a region is sometimes thought of in terms of a smooth contour surface that can adequately be described by isopleths drawn using a uniform grid of receptors, in fact the surface of the contour is often broken by spikes of high concentration at points near a few very large sources. Isopleths will not display these spikes unless a substantial number of receptors have deliberately been placed near these sources. If the modeler is unlucky, small changes in receptor location will cause a receptor to move from outside to inside the spike, or vice versa, causing a considerable distortion in the model results. The same is, of course, also true with respect to the location of pollution measuring stations.

The importance of the Rollback technique, which is dependent on a single maximum concentration for determining the required reduction in regional emissions, is one reason why this spiking problem is worth further investigation. Another is the interpretation of an "air quality standard" which demands that every point in the region be below a given concentration level.

Under the present Rollback definition, the stringency of the emission standards required will be dependent on the precise location of the pollutant measuring stations. Furthermore, since it is normal to discard some percentage of the measuring station data as inadequate, a considerable opportunity exists for some judicious juggling of results.

When modeling is used, and emission reduction is no longer dependent upon the Rollback reduction factor, the emission standards are still subject to this locational sensitivity. Most control strategies are designed to insure that every receptor in the region measures a concentration less than the air quality standard. One receptor grid may result in considerably different control requirements than another, because of the possibility of sliding into or out of a concentration spike.

As a partial solution to this problem, precise guidelines should be formulated and issued on such matters as the location of pollutant measuring stations, required receptor spacing around major sources, and acceptance/rejection of measured data. If a requirement for sharply decreased receptor spacing around potential spikes is formulated, then the question of the meaning of "satisfying an air quality standard" should be reopened....since such a receptor pattern will degrade a region's calculated air quality.

Finally, the reliance of Rollback on the concentration at a single point should be reconsidered in the light of the sensitivity of the measured "maximum concentration" to location of the measuring stations. In those cases where the number of stations is ample enough to permit it, an averaging technique employing a percentage of the highest measured concentrations might be considered. To compensate for the lower "maximum" this will produce, the reduction factor R might be calculated in a more severe fashion.

2.5.2 Least-Cost Control

The potential cost saving of a least-cost air pollution control strategy which is implied by this study is substantial enough to justify further investigation of this means of control. The present study has the following shortcomings:

- The "conventional source-category strategy" used for comparison with the least-cost strategy does not represent the lowest-cost "uniformly applied" strategy able to achieve the selected air quality standard.
- The study covered particulate control only.
- Area source control costs incurred by the conventional strategy were not measured (the least-cost strategy incurred zero area source control costs).
- The least-cost strategy does not include control of all point and area sources and thus does not necessarily represent an absolute minimum cost solution.
- The receptor grid used by the least-cost model did not include a number of high concentration locations which, if included, could theoretically alter the results.

- Control cost versus percentage of control was represented by a piece-wise linear function using only two line segments.

Several of the objections could be removed by increasing the capacity of the Linear Programming Model to include more receptors and sources and a better representation of control costs. Area source control costs could be approximated using available data. IPP could be used to search for an (approximately) least-cost version of a source-category strategy. Finally, since the controlled emissions of the industrial plants are known (they are calculated by the linear programming model), the ability to scale point source emissions in IPP would allow the generation of an "after least-cost control" diffusion model run which could be directly compared to competing strategies.

If sufficient interest is generated in a least-cost solution to the control of air quality, it is recommended that the above steps be taken to clarify the advantages and disadvantages of this method of control relative to the more common uniform application of emission standards.

3.0 EFFECTS OF CHANGING LAND USE

3.1 DISCUSSION

The purpose of this section is to present a method by which a diffusion model can be used as a tool for predicting the air quality effects of changing land use. Use of a diffusion model under standard operating procedures would normally be too expensive to justify the continuous re-running of the model to investigate many alternate land use changes. However, the diffusion model can be run with different possibilities of land use development "built into" the same run; this mode of operation is discussed in Sections 1.2 and 3.2.

The value of such a procedure is unquestionable. Many urban areas are beginning to ask whether good air quality and continued industrial and residential development, at increasing intensities, are compatible. Strict emission standards are currently being enforced or are being formulated which will reduce pollutant concentrations below levels specified by law. However, continued growth will cause air quality to degrade unless land use patterns are strictly controlled and the consequences of growth are thoroughly understood.

The method of air quality prediction presented here has all the problems of the standard diffusion model - lack of adequate source data, poor calibration due to measuring station inaccuracies, etc....plus a few of its own, such as degraded calibration due to the establishment of sources in new locations and the inability to exactly simulate effective stack height (except in a few restricted applications). It is felt, however, that the results will be useful enough to the land use planner and air pollution control agency to warrant further study.

The "Land Use Prediction Model" is applied to 10 scenarios in the St. Louis area defined in Figure 3-1 (this area is somewhat smaller* than the St. Louis Air Quality Control Region, and consists of that area within the "cordon line" of the East-West Gateway Transportation Study). The first 7 scenarios depict the addition of a major new powerplant to the region at 7 alternate sites. The remaining scenarios depict a dispersal of sources from the central area to the periphery of the region.

* However, the emission source file used in the analysis is the same as that used for the three strategies discussed in Section 2.0, and therefore the diffusion model can include areas up to that enclosed by the Air Quality Control Region.

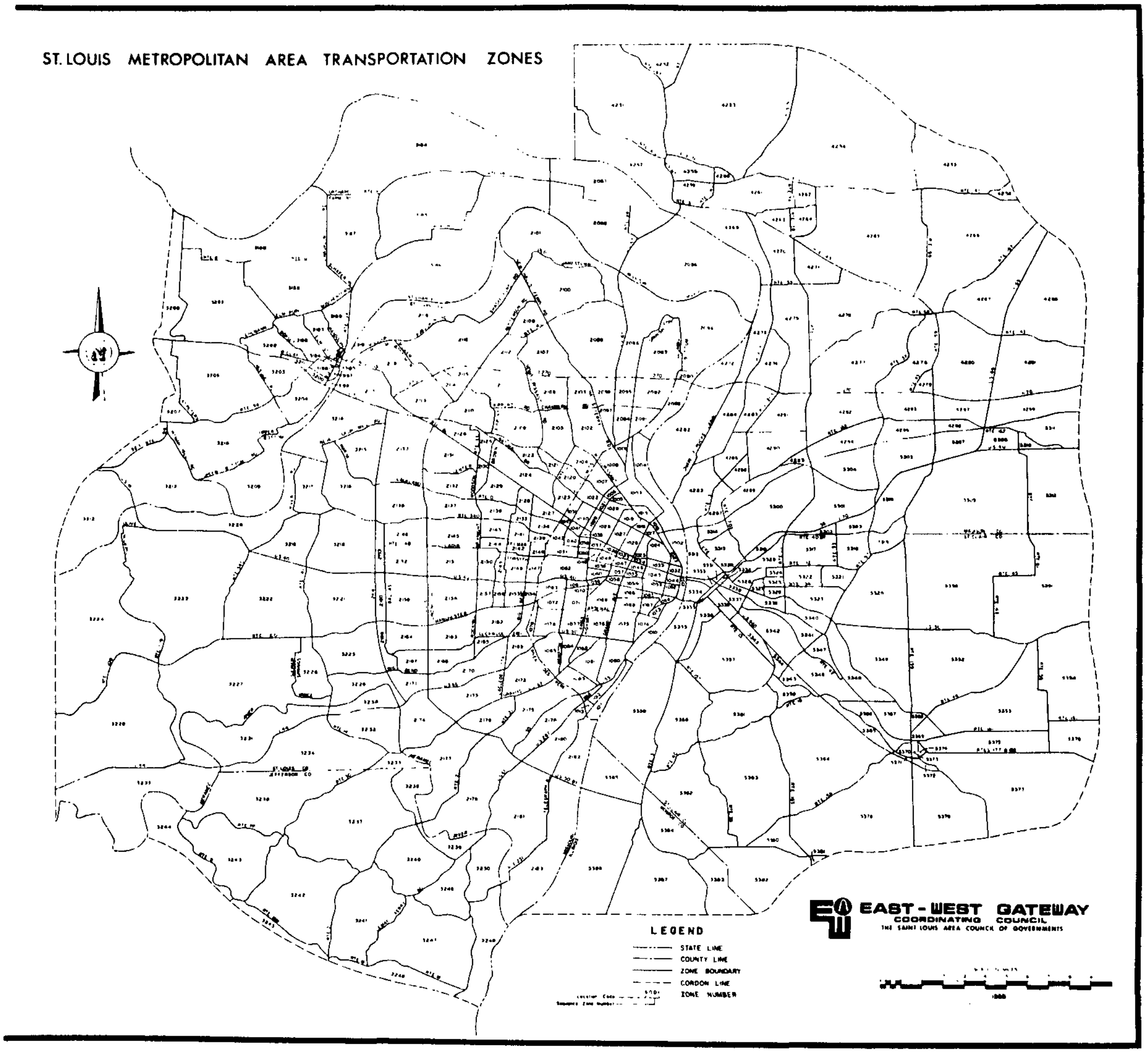


Figure 3-1 St.Louis Study Area

3.2 METHODOLOGY

3.2.1 Review of Modeling Procedure

The procedure for utilizing the diffusion model as a predictive tool is an extremely simple one. As discussed in Section 1.2, the diffusion model is run with a source file consisting of all existing point and area sources plus an assortment of "dummy" point and area sources which have emissions on the order of .001 tons per day or less. These dummy sources should be placed in locations where growth is postulated (according to growth projections, plant relocation schemes, land use plans, etc.). By using the Implementation Planning Program Strategy Model (in a "Null Standard" mode with point and area source scaling), or else a program specifically designed for the purpose, the diffusion model results may be manipulated so as to scale any source's emissions up or down. Sources can thus be "created" by scaling a dummy source up to a significant emission level, or "destroyed" by scaling downwards. Each dummy source has a specified "Effective Stack Height" (real stack height plus plume rise) assigned to it; any potential growth location can accommodate a range of potential plant types by placing several dummy sources one on top of the other, each with a different height. One source at a time can be "activated" to duplicate a large powerplant, medium sized industrial plant, etc. A real source can then be "relocated" to a new position by scaling it down to zero emissions and scaling up the appropriate dummy to duplicate its original emissions.

3.2.2 Basis for Procedure

The atmospheric diffusion model used in this study is based upon a diffusion model developed by Martin and Tikvart (1968). The basic output of the model is in the form of calculated long term average pollutant concentrations at ground level. The model calculates concentrations downwind from a set of point and area sources on the basis of the Pasquill (1962) point source formulation; the plume rise equation used in the model is due to Holland (1953).

The uncalibrated diffusion model has multiplicative and additive properties which allow its use in this analysis:

3.2.2.1 Multiplicative Property of Diffusion Model

If one assumes that all stack parameters - stack diameter and height, gas temperature and velocity - are kept constant.....

If a source Q at location L with emissions E produces an increment of ground level concentration C_i^Q at the i^{th} receptor (in other words, if Q is the only source in the region, receptor i will measure a ground level concentration of C_i^Q),

Then if source Q increases in size so that it has emissions N*E, it will produce an increment of ground level concentration $N*C_i^Q$

In other words,

SCALING THE EMISSIONS OF A SOURCE UP OR DOWN SCALES THE RECEPTOR CONTRIBUTIONS OF THAT SOURCE BY THE SAME FACTOR.

3.2.2.2 Additive Property of Diffusion Model

If a diffusion model is run twice-keeping the receptor grid the same-for N1 sources the first time, and for N2 sources the second.....

And assuming that the ground level concentrations computed at the i^{th} receptor are $C_i(1)$ and $C_i(2)$, respectively.....

Then the diffusion model run for the (N1 + N2) sources will yield concentrations at the i^{th} receptor of

$$C_i(1) + C_i(2)$$

The additive character of the diffusion model allows any portion of the emission source file which the modeler wishes to leave unchanged to be run separately from the "variable" portion of the file, i.e., that portion which will be scaled. Thus, the program which accomplishes the scaling need not handle those sources which remain constant. Under certain circumstances,* this separation will considerably shorten the running time of the secondary scaling program.

3.2.3 Further Details of Procedure

Figure 3-2 presents a flow diagram of the modeling procedure used for this study. The additive property of the diffusion model, as described above, is used to create a matrix of "base" concentrations and one of "variable" concentrations which can be added to produce the actual air quality matrix resulting from a given strategy being imposed on the "variable" emission sources. The calibration of the concentrations is conducted after addition of the two matrices.

*For instance, when the IPP "Strategy Model" is used for scaling.

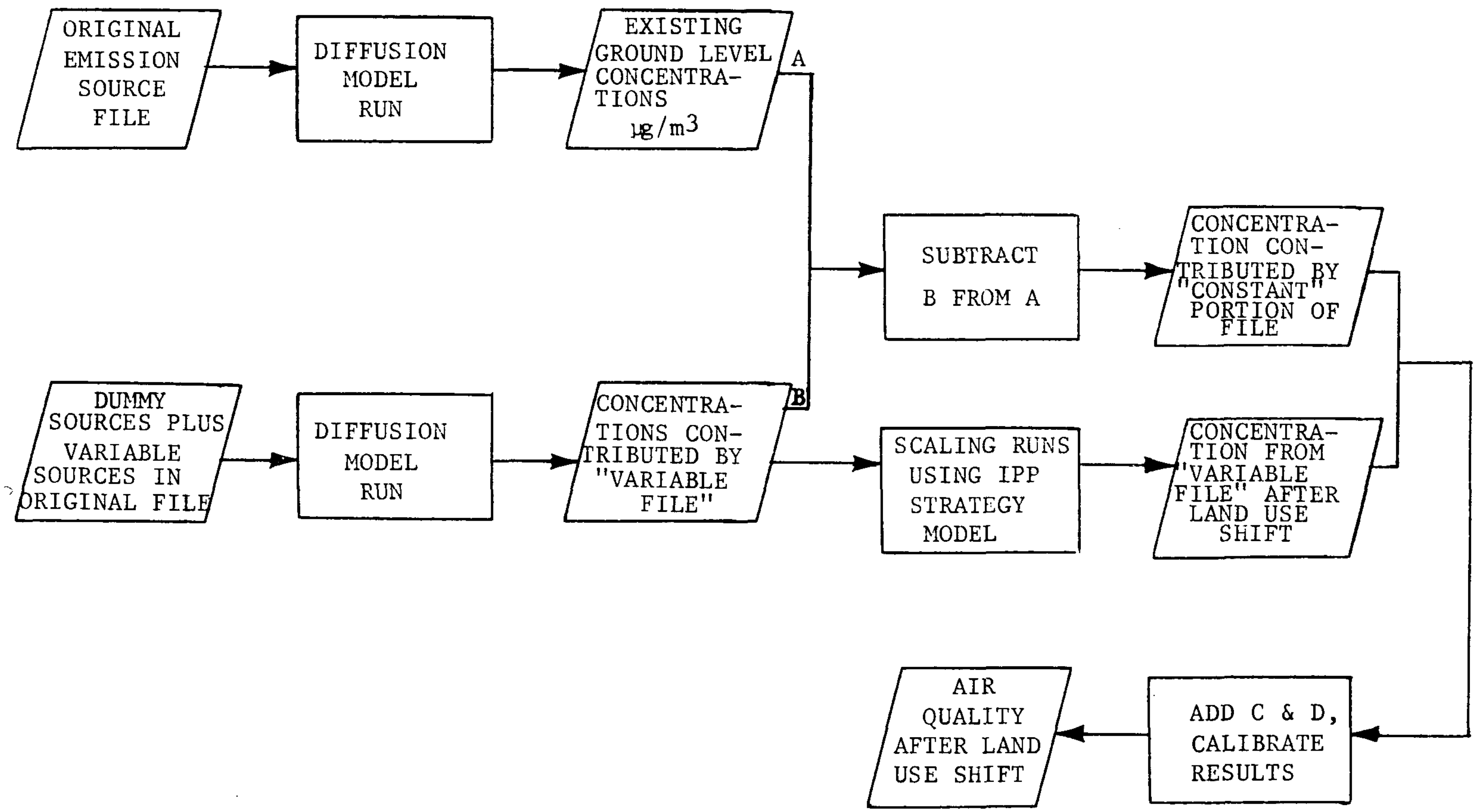


Figure 3-2. Prediction Model Flow Chart.

The reason for separating the source file in this manner is that a considerable portion of the point and area sources in the original file may be considered as too small to be included as variables in a (necessarily coarse) land use projection study, or else may have stabilized to a sufficient degree so that they may be considered constant during a modest time increment. It is convenient to remove these sources from the scaling runs so as to minimize the storage needs of the scaling program and to reduce run time.

3.2.4 Construction of the Emission Source File

The basic emission source file used in this study is the same as that used for the Emission Control Strategies Study discussed previously...... the St. Louis AQCR emission inventory provided by the Office of Air Programs and subsequently modified by TRW. To it have been added 55 dummy sources... 43 point sources and 12 area sources.....at 18 locations.

In order to decide where to place the dummy sources, socio-economic data for 1966 and projections for 1990 (supplied by the East-West Gateway Coordinating Council, St. Louis, Illinois) on industrial employment and residential population were investigated. For the most part, dummy sources were placed in sparsely populated areas and/or areas where substantial new industrial growth was expected to occur.....obviously, if scenarios different from those investigated had been used, different locations might have been chosen.

Table 3-1 lists the dummy sources added to the file. A computation of the effective stack heights of every large point source in the AQCR indicated that the large majority of sources could be accommodated by dummy

Table 3-1 . Dummy Source File

No.	Location	Characteristic of Location	Effective Stack Height*
LARGE POWER PLANTS			
1	(154,210)	Growing Industrial Area	-**
2	(155,245)	Industrial/Commercial	-
3	(151.5,216)	High Density Industrial	-
4	(113,215)	Future Industrial Area	-
5	(115,237)	Farmland	-
6	(152,199)	Farmland	-
7	(179.5,238)	Farmland	-
INDUSTRIAL PARKS (5 KM^2 AREA SOURCES)			
8	(110,224)	Underdeveloped	75 meters
9	(110,224)	Underdeveloped	140 m
10	(152,199)	Farmland	75 m
11	(152,199)	Farmland	140 m
12	(115,237)	Farmland	75 m
13	(115,237)	Farmland	140 m
14	(172,249)	Farmland	75 m
15	(172,249)	Farmland	140 m
16	(171,198)	Farmland	75 m
17	(171,198)	Farmland	140 m
18	(164,241)	Farmland, Near	75 m
19	(164,241)	Secondary Industrial Center	140 m
INDUSTRIAL POINT SOURCES			
20	(110,224)	Farmland	75 m
21	(110,224)	Farmland	140 m
22	(110,224)	Farmland	280 m
23	(152,199)	Farmland	75 m
24	(152,199)	Farmland	140 m
25	(115,237)	Farmland	75 m
26	(115,237)	Farmland	140 m

(contd.)

* Based on plume rise due to Holland (1953).
**Actual stack parameters were used in file.

Table 3-1. Dummy Source File (contd.)

No.	Location	Characteristic of Location	Effective Stack Height
INDUSTRIAL POINT SOURCES (contd.)			
27	(125,244)	Farmland	75 meters
28	(125,244)	Farmland	140 m
29	(125,244)	Farmland	280 m
30	(172,249)	Farmland	75 m
31	(172,249)	Farmland	140 m
32	(179.5,238)	Farmland	75 m
33	(179.5,238)	Farmland	140 m
34	(171,198)	Farmland	75 m
35	(171,198)	Farmland	140 m
36	(171,198)	Farmland	280 m
37	(181,204)	Farmland	75 m
38	(181,204)	Farmland	140 m
39	(113,215)	Undeveloped/farmland,	75 m
40	(113,215)	future industrial area.	140 m
41	(119,214)	Supposed to gain	75 m
42	(119,214)	substantial industry	140 m
43	(119,214)	by 1990.	280 m
44	(116,208)	Undeveloped	75 m
45	(116,208)	Undeveloped	140 m
46	(154,210)	Industrial	75 m
47	(154,210)	Industrial	140 m
48	(150,230)	Industrial	75 m
49	(150,230)	Industrial	140 m
50	(130,190)	Largely Undeveloped	75 m
51	(130,190)	Largely Undeveloped	140 m
52	(138,245)	Farmland	75 m
53	(138,245)	Farmland	140 m
54	(164,241)	Farmland, near secondary	75 m
55	(164,241)	industrial center.	140 m

sources with heights of 75, 140, or 280 meters without incurring errors of more than 20 meters. Sources 1 through 7, the new powerplants, were modeled more precisely:

Actual stack height	= 125 meters
Temperature	= 450°K
Stack diameter	= 8 meters
Gas velocity	= 20 meters/second

After scaling, these powerplant's emissions will be 250 and 75 Tons/Day for SO_2 and particulates, respectively.

Figure 3-3 shows the locations of the dummy sources.

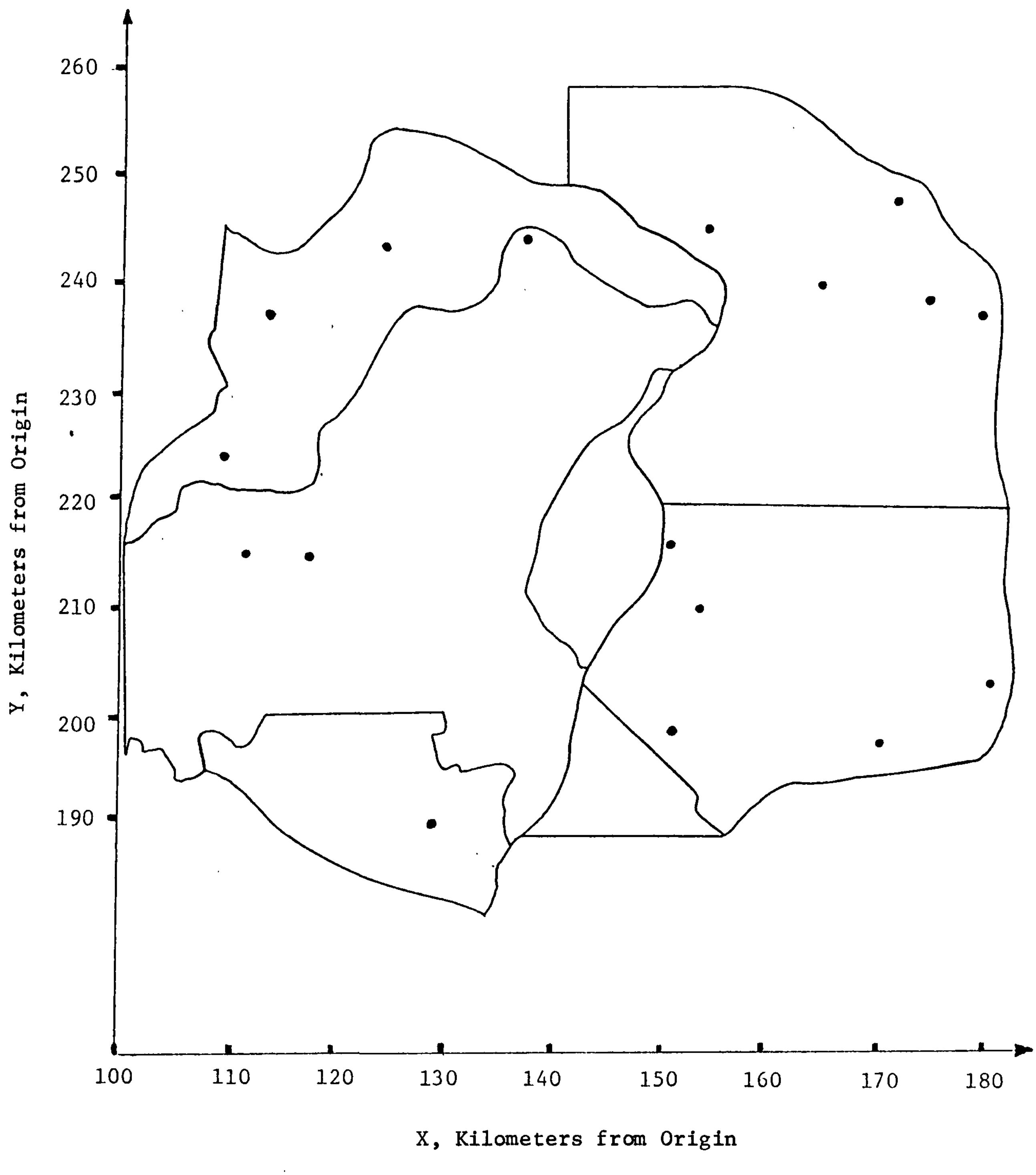


Figure 3-3. Location of Dummy Sources

3.2.5 Setting Up the Diffusion Model

The selection of a receptor net for the diffusion model should be based on the "scenarios" to be investigated, the nature of the source file and location of the major sources, and the method by which the air qualities resulting from the scenarios are to be compared. Ordinarily, receptor nets are set up so that spacing between receptors is great in those regions where few sources are located, and small in those areas of highest industrial and/or residential acitvity. If resulting air quality matrices are to be compared using some kind of cost/benefit model, or by a comparison of [(people within receptor "zone")*(concentration)] factors, a receptor net of this type is useful. However, if the comparison is to be made on a simplified basis, perhaps by counting the number of receptors measuring in various ranges of concentration, then a net of evenly spaced receptors might be selected. In any case, the problem of "scoring" the results of a diffusion model run.....which is essentially the same problem being addressed by cost/benefit models of air pollution.....is an agonizing one, and one which is often avoided by ignoring everything but the maximum concentration and calling that concentration the "air quality" achieved.

The receptor net selected for this study consists of a uniformly spaced grid whose corners are (x, y) = (100, 170), (100, 261), (191, 261), (191,170) (see Figure 3-4). There are 196 receptors in all, spaced 7 kilometers apart. The grid was selected because it covers the area in question reasonably effectively with a minimum number of receptors, thus minimizing computer time. Uniform spacing was used to allow a fair

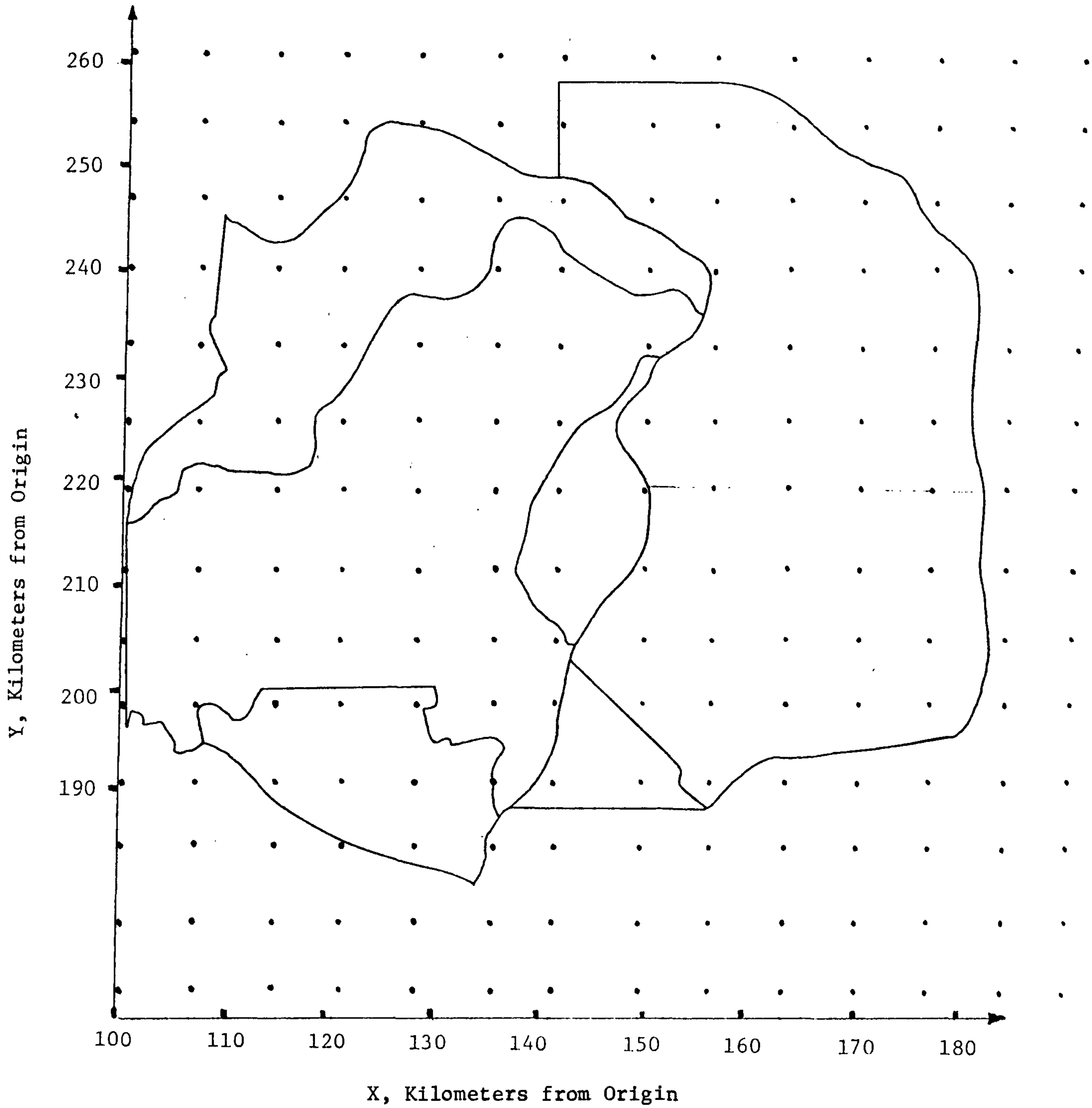


Figure 3-4. Diffusion Model Receptor Net

comparison of air quality results according to the number of receptors in each concentration range, as discussed above. For the purposes of a more sophisticated scoring system, or for the use of a few different types of scoring, a receptor net could be constructed which combined a uniformly spaced grid with additional receptors at selected locations. The different scoring systems would use only those receptor measurements which were applicable and would ignore the rest.

3.2.6 Scenarios

As discussed previously, the scenarios investigated in this study are:

- Adding a large new power plant to the region.
- Dispersing industry to the suburbs.

The first seven model runs involve the placing of the new plant in each of the "Large Powerplant" locations noted in Table 3-1, one at a time. This is accomplished as previously described, by scaling up the appropriate dummy point source and leaving the others unchanged. Four of the seven areas are very sparsely populated and thus should have no present pollution problem. The remaining areas are all developed to some extent, with one being in the core area.

The remaining three runs enact the "dispersal of industry." A number of large point sources in the region's central area are scaled down to simulate their closing, while dummy sources on the outskirts of the area are scaled up to duplicate the original sources. Table 3-2 lists the sources involved in the "relocation." These sources include 573.89

Table 3-2 . Emission Sources to be Relocated

No.	Location	SIC Code (Process)*	Emissions (SO_2/Part) Tons/Day	Effective Stack Height, Meters
1	150,223	2041(1)	0/11.37	69.8
2	150,223.4	2041(1)	0/17.15	155.2
3	156,218	2816(0)	2.56/9.67	79.5
4	152.1,214.5	2819(0)	32.75/6.00	74.7
5	150,215	2819(0)	32.80/10.70	45.8
6	161,241	2911(1)	6.85/6.00	91.6
7	161,241	2911(0)	17.67/4.72	89.5
8	152.5,214	2911(2)	19.00/.42	50.3
9	156,225	3312(0)	1.12/7.86	66.6
10	151.2,218.6	4911(0)	46.20/11.45	145.4
11	150.6,215	4911(0)	40.30/4.68	144.3
12	151.5,222	4911(0)	115.00/36.61	279.8
13	155.5,244	4911(0)	62.13/80.00	99.9
14	155.1,244	4911(0)	45.60/6.92	120.0
15	155.1,244	4911(0)	142.00/32.50	120.3

* 2041(1) Feed and Grain Mill Products
2816(0) Inorganic Pigments-Boiler
2819(0) Inorganic Industrial Chemicals-Boiler
2911(0) Petroleum Refinery-Boiler
2911(1) Petroleum Refinery-Fluid Catalyst
2911(2) Petroleum Refinery-Moving Bed Catalyst
3312(0) Iron and Steel-Boiler
4911(0) Power Plant

tons/day of SO_2 and 246.05 tons/day of particulates (respectively about 35 percent and 50 percent of total emissions).

Runs 8 and 9 place all the sources to be relocated in industrial groupings or parks. Referring back to table 3-1,

Run 8 relocates all sources to 3 locations:

1. Dummy sources 8, 9, and 22
2. Dummy sources 16 and 17
3. Dummy sources 14 and 15

Run 9 relocates all sources to 4 locations:

1. Dummy sources 18 and 19
2. Dummy sources 10 and 11
3. Dummy sources 12 and 13
4. Dummy source 36.

Run 10 establishes a nearly 1 to 1 relationship of original point sources and dummy point sources. The object is a maximum dispersal of point sources throughout the region. Table 3-3 presents the correspondence between the two source files.

3.2.7 Model Shortcomings

As briefly noted in Section 3.1, the procedure described in this section is subject to all the inaccuracies of the diffusion model it is based on, as well as to a few additional inaccuracies resulting from the prediction procedure.

Some of the major deficiencies of the diffusion model are:

- Accurate emission and stack data are difficult to acquire.
- The calibration procedure has only two degrees of freedom.

Table 3-3. Strategy 10 - Maximum Dispersal of Point Sources

Original Source No. (from Table 3-2)	Corresponding Dummy Point Source (from Table 3-1)
1	23
2	24
3	44
4	25
5	39
6	50
7	50
8	27
9	37
10	33
11	35
12	22
13	52
14	31
15	31

- Measured air quality data for calibration is often of limited accuracy.
- The diffusion equations do not fully explain the physical phenomena of diffusion.
- The model only accounts for average annual conditions (short range conditions can be predicted only statistically).

The prediction procedure adds the following inaccuracies (some of which may be corrected by increasing the scope of the procedure; an asterisk indicates this possibility):

- Since the calibration procedure accounts (somewhat) for topographical features of a region (the theoretical model assumes a flat plain), the calibration constants are tied to the locations of the emission sources. Adding new plant locations should change the calibration constants, but this effect cannot be accounted for in the procedure.
- The use of dummy sources introduces an error due to the difference between the dummy's effective stack height and the actual effective stack height of the source the dummy is to replace (in a plant relocation scheme).
- * The use of effective stack heights forces the model to average diffusion parameters over all atmospheric stability classes.
- * Relocation of industry will certainly be accompanied by shifts in traffic and residential development, neither of which are accounted for in the plant relocation "scenarios."

3.3 RESULTS

Three figures of merit are utilized to measure the effect of the 10 Prediction Model scenarios:

- Maximum concentration measured in the region.
- Average concentration of the "worst" 20 receptors.
- Number of receptors in different ranges of concentration (60-70 $\mu g/m^3$, 70-80 $\mu g/m^3$, etc.).

Although the maximum concentration is often used to denote "air quality," the average value should give a more meaningful idea of the true effect of the scenarios.

3.3.1 Where to Locate a New Power Plant

Tables 3-4 and 3-5 present the results of the first seven runs of the model, each of which represents the placing of a major new power plant with a large effective stack height on a new site. As was inevitable, the results uniformly show a degradation of air quality, although the effects are quite mild.

3.3.2 Dispersal of Industry

Tables 3-6 and 3-7 present the results of the latter three runs of the model; runs ("scenarios") 8 and 9 represent the relocation of several centrally-located point sources to a few industrial parks on the periphery of the region; run 10 represents a "maximum dispersal" scenario where the same point sources are relocated separately to sites scattered around the periphery. The results are unusual in that the average concentration at the 20 "worst" receptors was higher, for particulates, than was the average before dispersal.

Table 3-4 . Where to Locate a New Power Plant; Air Quality Results

STRATEGY	CONCENTRATION AT WORST RECEPTOR, μg/m3	AVERAGE* CONCENTRATION AT 20 WORST RECEPTORS, μg/m3
(SO_2)		
EXISTING	85.94	57.63
1	86.45	61.80
2	86.15	61.66
3	86.27	61.78
4	86.28	61.64
5	86.33	61.68
6	86.60	61.77
7	86.04	61.52
(Particulates)		
EXISTING	163.85	112.09
1	164.24	112.43
2	164.10	112.28
3	164.26	112.41
4	164.15	112.32
5*		
6	164.24	112.42
7	163.96	112.22

* Simple arithmetic average of 20 highest concentrations in strategy diffusion output.

** Input error disqualified results.

Table 3-5. Where to Locate a New Power Plant; Number of Receptors in Different Ranges of Air Quality

SO_2						
STRATEGY # / RANGE ($\mu g/m^3$)	30-40	40-50	50-60	60-70	70-80	80-90
EXISTING	135	41	11	5	2	2
1	132	44	11	5	2	2
2	134	43	11	5	2	2
3	132	45	11	4	3	2
4	131	45	11	5	2	2
5	132	43	11	5	2	2
6	133	43	11	4	2	2
7	133	43	11	5	2	2

Particulates								
STRATEGY # / RANGE ($\mu g/m^3$)	60-70	70-80	80-90	90-100	100-110	110-120	120-130	>130
EXISTING	75	68	28	12	6	1	2	4
1	74	69	28	11	7	1	2	4
2	75	68	28	11	7	1	2	4
3	74	69	28	11	7	1	2	4
4	74	69	28	11	7	1	2	4
5*								
6	74	69	28	11	7	1	2	4
7	75	68	28	11	7	1	2	4

*Input error disqualified results.

Table 3-6. Dispersal of Industry; Air Quality Results

STRATEGY	CONCENTRATION AT WORST RECEPTOR, $\mu g/m^3$	AVERAGE CONCENTRATION AT 20 WORST RECEPTORS, $\mu g/m^3$
(SO_2)		
NULL	85.94	61.38
8	72.10	54.59
9	73.94	56.67
10	70.84	55.56
(Particulates)		
NULL	163.87	112.09
8	155.44	114.81
9	156.72	116.93
10	155.09	115.79

Table 3-7. Dispersal of Industry; Number of Receptors in Different Ranges of Air Quality

SO_2						
STRATEGY # / RANGE ($\mu g/m^3$)	30-40	40-50	50-60	60-70	70-80	80-90
EXISTING	135	41	11	5	2	2
8	115	64	12	5	1	0
9	123	54	11	6	2	0
10	107	73	11	4	1	0

Particulates								
STRATEGY # / RANGE ($\mu g/m^3$)	60-70	70-80	80-90	90-100	100-110	110-120	120-130	>130
EXISTING	75	68	28	12	6	1	2	4
8	34	71	49	24	7	3	5	2
9	34	75	44	24	6	5	6	2
10	41	57	59	20	9	5	2	3

3.3.3 Comparison of Diffusion Model Results With Those of Section 2

The use of separate diffusion model runs (with different receptor grids) for essentially the same area presented an opportunity for an interesting comparison. A comparison of two of the three "figures of merit", the maximum concentration and the average at the 20 "worst" receptors, indicates that both values differ significantly (Table 3-8). This difference is certainly a function of the grid spacing and location; for instance, the grid used in Section 2.0 has a greater number of receptors in areas of high concentration, and therefore may be expected to have a larger average concentration at the 20 "worst" receptors.

Table 3-8. Comparison of the Two Diffusion Models

- Section 2.0 - Emission Control Strategies Comparison.
- Section 3.0 - Land Use Model.

	SECTION 2.0	SECTION 3.0
SO_2		
• Maximum concentration, $\mu g/m^3$	144.2	85.9
• Average concentration at 20 "worst" receptors, $\mu g/m^3$	85.9	61.4
Particulates		
• Maximum concentration, $\mu g/m^3$	170.6	163.9
• Average concentration at 20 "worst" receptors, $\mu g/m^3$	138.2	112.1

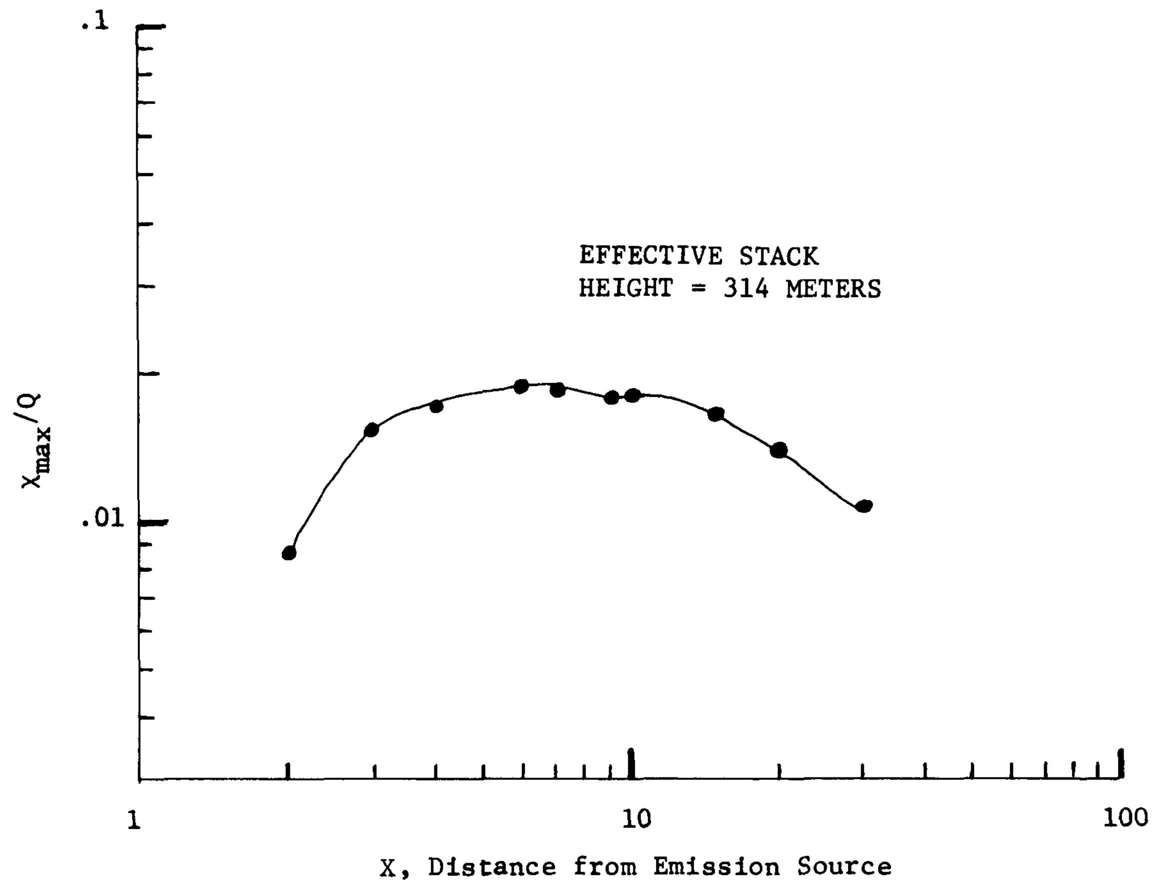
3.4 CONCLUSIONS

The analyses carried out so far indicate that changes in air quality patterns caused by the two sets of scenarios would be quite mild.

3.4.1 Where To Locate A New Powerplant

The results for the addition of a powerplant to the region suggest that the precise location of the particular powerplant investigated may not be extremely important from a regional air quality viewpoint. This conclusion is undoubtedly due to the very large effective stack height (about 400 meters), which was selected for analytical purposes as being representative of the larger power plants in the region.

A sensitivity analysis conducted in parallel with this study produced Figure 3-5, which shows the distribution of pollutants from a 314 meter (effective) stack height, the largest available from the analysis. A 250 Ton/Day emission, typical of the SO_2 emissions of the larger St. Louis powerplants, would have a maximum incremental effect of about 5 $\mu g/m^3$ between 5 and 10 kilometers from the source. The effect of a 400 meter (effective) stack would be somewhat less. Furthermore, use of the calibration coefficients of the St. Louis diffusion model requires that this increment be multiplied by .3 for SO_2 and .6 for particulates to determine the true effects of the plant. Thus, the maximum incremental effect of the power plant used in the analysis would be less than .9 $\mu g/m^3$ for particulates and 1.5 $\mu g/m^3$ for SO_2 (daily SO_2 emissions = 250 Tons, daily particulate emissions = 75 Tons). In order to differentiate between alternate power plant scenarios, the model would have to be rerun with a lower effective stack



χ_{max} = Maximum incremental concentration, $\mu g/m^3$

Q = Emission rate, Tons/Day

Figure 3-5. Diffusion of Pollutants From a Point Source height; time constraints precluded this rerun under the existing contract.

Any conclusions drawn from these results about the use of tall stacks should be tempered with the following two considerations:

- Air quality results given by the modeling process are in terms of average annual concentrations. Air pollution incidents in the past have shown that large amounts of pollutants emitted by tall stacks can cause very high short-term impacts on ground level concentrations during periods of atmospheric stagnation.
- Although the long-term impact of any one tall stack powerplant is not high at any single location, global considerations accounting for all emission sources preclude the use of tall stacks as a <u>sole</u> solution to air pollution problems. The additive nature of the pollutant contributions from each source in an area demands the use of emission control to achieve acceptable air quality levels.

3.4.2 Dispersal of Industry

All three industry dispersal scenarios succeeded in lowering the maximum concentrations of both SO_2 and particulates measured in the region. The "maximum dispersal" scenario (#10) achieved the lowest concentrations for both pollutants. In addition, significant reductions in the average SO_2 concentrations of the 20 "worst" receptors were achieved in all three scenarios. However, these average concentrations were <u>higher</u> for the particulate scenario runs, an occurrence not easily explained by the nature of the locational shifts made. The wide receptor spacing of this preliminary model makes it rather susceptible to the kind of error described in Section 3.4.3, where a shift in location of the receptors or sources can cause the receptors to slide into or out of a concentration peak. It is possible that the receptor grid is missing several such peaks in the "null" scenario (sources in their original positions).

3.5 RECOMMENDATION

Before the air quality prediction procedure outlined in this section can be accepted as a useful planning tool, certain questions about its accuracy must be answered.

Of primary importance is the sensitivity of the predictions to the approximations inherent in the use of the dummy sources. One important approximation is the use of a few effective stack heights to represent the entire spectrum. Another is the error caused by the use of these heights instead of using actual stack parameters. The sensitivity analysis noted in Section 3.4 may provide useful data for analyzing the degree of error represented by these approximations, and defining procedures to overcome or minimize these errors.

Another issue involves the sensitivity of the diffusion model calibration constants to shifts in major plant locations. At first glance, it seems that an analysis which looks at two time periods in the history of a region would be necessary to establish an order of magnitude sensitivity of calibration to plant location. It is possible that sufficient data may not be available for such a study, and it is suggested that a theoretical basis for establishing such sensitivity may be available from the work being done on diffusion models which can account for topography.

Finally, it would be useful to construct an actual model (rather than using the "wired-together" procedure that was necessary for this brief analysis) and to run some more detailed scenarios in order to iron out correct modeling procedures and to better judge the model's usefulness. In regard to the latter point, an accurate comparison could be made of actual computer time using the model and using the laborious procedure of running a new diffusion model for every scenario.

4.0 REFERENCES

1. TRW Systems Group, Air Quality Implementation Planning Program, November 1970.

2. Dickerson, William D., Sensitivity Analysis of Selected Air Quality Implementation Planning Program Input Parameters, TRW Systems Group, June 1971.

3. Diamante, John and Goldstein, Burton, Demonstration of a Regional Air Pollution Cost/Benefit Model, TRW Systems Group, June 1971.

4. Martin, Delance O. and Joseph A. Tikvart, "A General Atmospheric Diffusion Model for Estimating the Effects on Air Quality of One or More Sources," APCA Journal (June 1968), pp. 68-148.

5. Pasquill, F., "The Estimation of the Dispersion of Windborne Material," Meteorol Magazine (1961), 90, 1063, pp. 33-49.

6. Holland, J. Z., "A Meteorological Survey of the Oak Ridge Area," Atomic Energy Commission Report ORO-99 (1953), pp. 554-559.

7. The Cost of Clean Air, Report to the 91st Congress, Document No. 91-65, U. S. Government Printing Office, Washington, D. C., March 1970.

8. Boudreaux, A. D. and Weidemann, W. E., Forecast of Socio-Economic Characteristics for the St. Louis Metropolitan Region, East-West Coordinating Council, January 1970.

APPENDIX A

APPENDIX A

SOURCE DECK LISTING FOR THE LEAST-COST MODEL

```
      PRØGRAM ØPT(INPUT,ØUTPUT,TAPE6=ØUTPUT)
      DIMENSIØN MI(45),ISTATE(30),NSTATE(30),REQ(30)
      DIMENSIØN BACK(30),V(75),X(45),CØ(30),EX(45)
      DIMENSIØN ØUTP(80)
      DIMENSIØN DLEVEL(15),RATE(30,4)
      DIMENSIØN C(45,30),CØST(30,4),QUAN(30,4),MR(75),MIC(30)
C SET QUAN(I,1):NØ CØNTRØL TØNS/DAY ØF ITH SØURCE
      DATA (QUAN(I),I=1,9)/6.25,5.7,11.37,17.15,5.09,4.21
     +,2.95,2.67,21.22/
      DATA (QUAN(I),I=10,18)/3.42,7.3,6.,10.7,6.,4.72,
     +2.9,3.28,3.68/
      DATA(QUAN(I),I=19,27)/3.72,7.6,5.,5.1,
     +11.9,80.,6.9,32.5,5.6/
      QUAN(7)=2.94
C SET QUAN(I,J+1):J TH NØDE REDUCTIØN (%) ØF ITH SØURCE
      DATA (QUAN(I),I=31,40)/75.,80.,2*75.,52.,
     +2*75.,76.,2*75./
      DATA (QUAN(I),I=41,48)/52.,68.,2*75.,52.,
     +2*75.,97./
      DATA (QUAN(I),I=49,57)/93.,63.,66.,74.,81.,
     +3*75.,93./
      DATA(QUAN(I),I=61,76)/7*99.,95.,7*99.,99.7/
      DATA(QUAN(I),I=77,87)/5*99.,92.4,2*99.,89.2,2*99./
C SET RATE(I,J): MARGINAL CØST/TØN ØN JTH SEGM'T ØF ITH SØURCE
      DATA(RATE(I),I=1,9)/16.,16.,11.,15.,
     +341.,19.,13.,600.,4./
      DATA(RATE(I),I=10,18)/34.,63.,32.,4.,128.,
     +58.,15.,2.,118./
      DATA(RATE(I),I=19,27)/214.,251.,86.,909.,
     +75.,5.,104.,39.,240./
      DATA(RATE(I),I=31,39)/73.75,57.68,184.25,
     +279.,1830.2,97.375,41.875,100.,20.5/
      DATA (RATE(I),I=40,48)/1172.5,79.85,111.84,
     +32.875,1064.375,72.745,321.77,10.25,464.5/
      DATA(RATE(I),I=49,57)/1138.,311.5,173.,
     +3138.65,201.5,17.375,4469.77,96.75,1312..5/
C SET NSTATE(I): # ØF SEGMENTS DESCRIBING CØST CURVE,ITH SØURCE
      DATA(NSTATE(I),I=1,30)/30*2/
      QUAN(68)=97 .1
C SET BACKGRØUDND AT DETECTØRS
      DATA(BACK(I),I=1,30)/30*0./
      RATE(38)=2114.02
C NS:# SØURCES   ND:#DETECTØRS
      NS=27
      ND=9
C
C
C
C
```

```
C SET INITIAL C(J,I): ITH SØURCE CØNTRIBUT. TØ JTH DETECTØR
      DATA (C(I),I=1,9)/.2474,.4390,.5946,.3839,
     +.8218,1.3172,.3694,2.0697,.8493/
      DATA (C(I),I=46,54)/.5665,1.0887,1.1673,.9735,
     +3.3816,1.5643,.6208,4.6410,.9989/
      DATA (C(I),I=91,99)/.1704,.2585,.4871,.3496,
     +.8201,2.3927,.3170,1.3263,1.0441/
      DATA (C(I),I=136,144)/.1520,.2511,.4491,.3298,
     +.5745,1.6024,.2899,1.0230,.7241/
      DATA (C(I),I=181,189)/.0409,.0659,.1187,.0896,
     +.1379,.4082,.0799,.2714,.1867/
      DATA (C(I),I=226,234)/.1466,.1613,.4204,.1970,
     +.4169,1.3011,.1902,.4576,1.3764/
      DATA (C(I),I=271,279)/.1364,.1788,.1606,.2064,
     +.2961,.2156,.4644,.6927,.2998/
      DATA (C(I),I=316,324)/.3129,.6614,.5079,.5582,
     +4.6555,.7306,.3573,1.6288,.3866/
      DATA (C(I),I=361,369)/.4851,.6668,.8131,.5697,
     +.8380,1.5646,.5512,.8457,1.5545/
      DATA (C(I),I=406,414)/.3190,.4439,.8794,.4445,
     +1.3501,1.6409,.2556,1.0757,.9003/
      DATA (C(I),I=451,459)/.5538,1.2900,.6937,2.0823,
     +3.2759,1.0177,1.1418,.9075,.4181/
      DATA (C(I),I=496,504)/.1174,.2471,.2457,.2412,
     +1.0650,.5721,.3518,1.7311,.2858/
      DATA (C(I),I=541,549)/1.1535,2.4376,2.1218,2.0666,
     +11.7449,2.8054,1.3655,8.8684,1.6711/
      DATA (C(I),I=586,594)/.3277,.3916,.4468,.3798,
     +.5778,.8371,.3282,.5581,1.5707/
      DATA (C(I),I=631,639)/ .0414,.0525,.0737,.0518,
     +.0817,.1353,.0867,.1535,.4334/
      DATA (C(I),I=676,684)/.2561,.4893,.5351,.4770,
     +1.2980,.7596,.3337,3.7392,.4330/
      DATA (C(I),I=721,729)/.2873,.4073,.8943,.2918,
     +.7211,.4216,.1726,.4516,1.8153/
      DATA (C(I),I=766,774)/ .0543,.0370,.0275,.0408,
     +.0311,.0244,.0204,.0125,.0113/
      DATA (C(I),I=811,819)/.1240,.0949,.0663,.0822,
     +.0604,.0528,.0659,.0334,.0230/
      DATA (C(I),I=856,864)/.0557,.0766,.0703,.0562,
     +.0500,.0564,.0559,.0321,.0256/
      DATA (C(I),I=901,909)/.0463,.1059,.1183,.1005,
     +.1897,.3325,.1157,.5858,.1480/
      DATA (C(I),I=946,954)/.0644,.1592,.1367,.1337,
     +.5420,.2957,.1813,.6209,.1292/
      DATA (C(I),I=991,999)/.0507,.0829,.1270,.1021,
     +.0996,.2920,.1182,.3253,.1704/
      DATA (C(I),I=1036,1044)/.5511,.6827,1.0907,.8398,
     +1.1527,2.1001,1.0032,1.6938,3.7068/
      DATA (C(I),I=1081,1089)/.0446,.0547,.0841,.0684,
     +.0929,.1617,.0811,.1338,.2748/
      DATA (C(I),I=1126,1134)/.2252,.2817,.4498,.3437,
     +.4791,.8643,.4014,.6682,1.3685/
      DATA (C(I),I=1171,1179)/.0133,.0125,.0128,.0175,
     +.0203,.0231,.0137,.0182,.0271/
```

```
C
C
C
C CØ NVERT C(J,I) TØ INFLUENCE CØEFFICIENTS
      DØ 177 I=1,NS
      DØ 177 J=1,ND
  177 C(J,I)=C(J,I)/QUAN(I,1)
  279 FØRMAT (9F7.4)
C
C
C
C
C
      DISPLAY *INPUT REQ. LEVELS*
      ACCEPT (REQ(I),I=1,ND)
C SET CØNSTANTS
C
      DISPLAY *REDUCED PRINT? (0 ØR 1):*
      ACCEPT IPRT
C
      NS1=NS+1
      NE1=NS+ND
      NS2=NE1+1
      NE2=NE1+NS
C
C SET INITIAL VALUES
C   DLEVEL:NØ CØNTRØL LEVELS  REQ:REQUIRED LEVELS
C   ISTATE:CURRENT CØST CURVE SEGMENT
C
      DØ 1 I=1,ND
      DLEVEL(I)=BACK(I)
    1 X(I)=REQ(I)-BACK(I)
      DØ 2 J=1,NS
      NST=NSTATE(J)+1
      ISTATE(J)=NST
C PRESET RESIDUAL ØUTPUT
      DØ 10 I=2,NST
      RATE(J,NST-I+2)=RATE(J,NST-I+1)
   10 QUAN(J,I)=QUAN(J,1)*(1.-QUAN(J,I)/100.)
C
      FACTØR=1.
      DØ 3 I=1,ND
      C(I,J)=C(I,J)*FACTØR
      DLEVEL(I)=DLEVEL(I)+C(I,J)*QUAN(J,1)
    3 X(I)=X(I)-QUAN(J,NST)*C(I,J)
      X(J+ND)=-QUAN(J,NST)+QUAN(J,NST-1)
      CØST(J,1)=0.
      DØ 9 I=2,NST
    9 CØST(J,I)=CØST(J,I-1)+RATE(J,I)*(QUAN(J,I-1)-QUAN(J,I))
      V(J)=RATE(J,NST)
C
      MR(J)=J
      MIC(J)=J
```

```
C
      ND1=ND+1
      DØ 14 I=ND1,NE1
   14 C(I,J)=0.
    2 C(J+ND,J)=1.
C
      DØ 4 I=NS1,NE2
      MR(I)=-(I-NS)
      MI(I-NS)=I
    4 V(I)=0.
      MEX=0
      DØ 990 I=1,NE1
      IF(X(I).LT.0.) DISPLAY *UNFEASIBLE*,I,X(I)
  990 IF(X(I).LT.0.) MEX=1
      IF(MEX.EQ.1) GØ TØ 99
C -----------------------------
C BEGIN LØØP:START WITH X,V,C,MR,MI,MIC
C     X:STATE VECTØR    V:VALUE VECTØR    C:CØNSTRAINT MATRIX
C     MR:MAPPING ØRIGINAL VECTØR TØ CURRENT LØCATIØN
C     MI:MAPPING BASIS VECTØR TØ ØRIGINAL VECTØR
C     MIC:MAPPING CØNSTRAINT VECTØR TØ ØRIGINAL VECTØR
C  FIRST NS VECTØRS IN ØRIGINAL SET ARE SØURCE PØLLUTIØN (TØNS)
C   ABØVE MINIMUM FØR CURRENT SEGMENT. NEXT ND VECTØRS ARE
C   EXCESS QUALITY AT DETECTØRS. NEXT NS VECTØRS ARE REMAINING
C   PØLLUTIØN ØUTPUT ØN CURRENT SEGMENT.
C
      IT=0
  140 CØNTINUE
      IF(MEX1.EQ.0) GØ TØ 179
      DØ 181 I=1,NE2
      IJ=MR(I)
      ØUTP(I)=0.
  181 IF(IJ.LT.0) ØUTP(I)=X(-IJ)
      WRITE (6,182) (ØUTP(I),I=1,NE2)
  182 FØRMAT(10E7.1)
  179 CØNTINUE
      IT=IT+1
      IF(IT.EQ.100) DISPLAY *IT=100:ENTERIT*
      IF(IT.GT.100) ACCEPT IT
C
```

```
C ---------------------------
C FIND VECTØR FØR INSERTIØN
      X2=0.
      DØ 19 K=1,NS
      IC=MIC(K)
   19 CØ(K)=V(IC)
      DØ 20 I=1,NE1
      IB=MI(I)
      IF(V(IB).EQ.0.) GØ TØ 20
      DØ 20 J=1,NS
      IF(C(I,J).NE.0.) CØ(J)=CØ(J)-C(I,J)*V(IB)
   20 CØNTINUE
C
C  CHECK NEIGHBØRING CØST CURVE SEGMENTS
      DØ 21 K=1,NS
      IF(CØ(K).LE.X2) GØ TØ 122
      X2=CØ(K)
      KMX=K
  122 IF(CØ(K).GT.0.) GØ TØ 21
      IC=MIC(K)
      IF(IC.GT.NE1) GØ TØ 27
      IF(IC.GT.NS) GØ TØ 21
      NST=ISTATE(IC)
      IF(NST.EQ.NSTATE(IC)+1) GØ TØ 21
      X1=-CØ(K)+V(IC)-RATE(IC,NST+1)
C
      IF(X1.LE.X2) GØ TØ 21
      GØ TØ 24
C
   27 NST=ISTATE(IC-NE1)
      IF(NST.EQ.2) GØ TØ 21
      IC=IC-NE1
      X1=-CØ(K)-V(IC)+RATE(IC,NST-1)
C
      IF(X1.LE.X2) GØ TØ 21
C
   24 KMX=-K
      X2=X1
   21 CØNTINUE
      IF(X2.LE.0.) GØ TØ 110
C
```

```
C -------------------------
C  KMX IS ENTERING VECTØR:IF NEG THEN CHANGE SEGMT.
C
      IF(KMX.LT.0) GØ TØ 35
      MD=0
C FIND VECTØR FØR REMØVAL
C MIN ØF X(J)/C(J,KMX)
C
      KMN=0
      DØ 22 J=1,NE1
      IF(C(J,KMX).LE.0.) GØ TØ 22
      TØT=X(J)/C(J,KMX)
      IF(KMN.EQ.0) XY=TØT+1
      IF(TØT.GT.XY) GØ TØ 22
      KMN=J
      XY=TØT
   22 CØNTINUE
      IF(KMN.EQ.0) GØ TØ 120
C
C KMN IS LEAVING VECTØR
C
C  -------------------------
C PERFØRM UPDATING
C
   37 CØNTINUE
C EX IS ØLD BASIS VECT IN NEW BASIS FØRMAT
      DØ 23 I=1,NE1
   23 EX(I)=-C(I,KMX)/C(KMN,KMX)
      EX(KMN)=EX(KMN)+1./C(KMN,KMX)
      K5=MIC(KMX)
      K6=MI(KMN)
C
C CØ IS CØNSTRAINT CØØRD IN ØLD BASIS VECTØR CØMPØNENT
      DØ 28 I=1,NS
   28 CØ(I)=C(KMN,I)
      DØ 25 I=1,NS
      IF(CØ(I).EQ.0.) GØ TØ 25
      DØ 26 J=1,NE1
   26 C(J,I)=C(J,I)+CØ(I)*EX(J)
   25 CØNTINUE
      DØ 207 J=1,NE1
  207 C(J,KMX)=EX(J)
      C(KMN,KMX)=EX(KMN)+1.
C UPDATE MAPPINGS
      IC=MI(KMN)
      MR(IC)=KMX
      MI(KMN)=MIC(KMX)
      MIC(KMX)=IC
      IC=MI(KMN)
      MR(IC)=-KMN
C
C NEW SØLUTIØN VECTØR
      IF(MD.EQ.1) GØ TØ 140
      X1=X(KMN)
      DØ 30 I=1,NE1
   30 X(I)=X(I)+EX(I)*X1
C LØØP BACK
      GØ TØ 140
```

```
C --------------------------
C CHANGE CØST CURVE SEGMENT
   35 KMX=-KMX
      MD=1
      KM=MIC(KMX)
      IF(KM.GT.NS) GØ TØ 36
      NST=ISTATE(KM)
      ISTATE(KM)=NST+1
      KMN=-MR(KM+NE1)
      X(KMN)=-QUAN(KM,NST+1) +QUAN(KM,NST)
      V(KM)=+RATE(KM,NST+1)
      GØ TØ 37
   36 IC=KM-NE1
      KMN=-MR(IC)
      NST=ISTATE(IC)
      ISTATE(IC)=NST-1
      X(KMN)=-QUAN(IC,NST-1)+QUAN(IC,NST-2)
      V(IC)=RATE(IC,NST-1)
      GØ TØ 37
C -------------------------
C ERRØR EXIT
  120 DISPLAY *UNBØUNDED SØLUTIØN*
      KMX=MIC(KMX)
      DISPLAY *EXIT VECT*,KMX,*ITER*,IT
      GØ TØ 99
C
C --------------------------
C FINAL SØLUTIØN ATTAINED
  110 CØNTINUE
      DISPLAY IT,*ITERATIØNS*
      DISPLAY * *
      DISPLAY *SUMMARY ØF RESULTS*
      DISPLAY *SØURCE LEVELS*
      DISPLAY *SØURCE #     %CUT    RESIDUAL(TN) CØST($)*
     +,*  RATE($/TN)*
      DØLLAR=0.
      DØ 201 I=1,NS
      ID=-MR(I)
      NST=ISTATE(I)
      NSTM=NSTATE(I)+1
      X1=0.
      IF(ID.GT.0) X1=-X(ID)*V(I)
      X1=CØST(I,NST)+X1
      X2=0.
      IF(ID.GT.0) X2=X(ID)
      X2=X2+QUAN(I,NST)
      DØLLAR=DØLLAR+X1
      X3=100.-100.*X2/QUAN(I,1)
      IF(IPRT*ID.LT.(NST-NSTM)*200) GØ TØ 476
      WRITE (6,204) I,NST,X3,X2,X1,V(I)
  476 CØNTINUE
  204 FØRMAT(2I4,F10.1,F8.2,2F10.1)
  201 CØNTINUE
```

```
      DISPLAY * *
      DISPLAY *RECEPTØRS:*
      DISPLAY *RECEPTØR  PRE       PØST       REQ     MARG CØST*
      DØ 205 I=1,ND
      X1=0.
      ID=-MR(I+NS)
      IF(ID.GT.0) X1=X(ID)
      X1=REQ(I)-X1
      X2 =REQ(I)
      X3=DLEVEL(I)
C
      X4=0.
      IF(ID.LT.0) X4=-CØ(-ID)
      WRITE (6,206) I,X3,X1,X2,X4
  206 FØRMAT(I4,4F10.2)
  205 CØNTINUE
      DISPLAY * *
      DISPLAY *TØTAL CØST:*,DØLLAR
   99 CØNTINUE
      END
```