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COST EVALUATION OF AIR POLLUTION CONTROL STANDARDS

M. F. Ruane

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by

Michael Frederick Ruane

ABSTRACT

A model is developed to describe the sulfur dioxide and particulate air pollution characteristics of a fossil fueled steam electric power plant. The model contains three stages. The first considers boiler emissions and the application of one of four parameterized abatement methods: wet limestone scrubbing, catalytic oxidation, magnesium oxide scrubbing, and the use of tall stacks. The second stage tests stack emissions and uses meteorological dispersion models, particularly the double gaussian model, to determine and test three hour, twenty-four hour and annual worst case ground level concentrations. The third stage calculates the performance of the abatement method used in terms of economics and resource costs.

The model can be used to determine feasible combinations of plant types, site types and abatement methods as support for a separate generation expansion model. It can also be used independently to study environmental and economic sensitivities to changes in air pollution standards.

General descriptions of the operation of the abatement methods and explanations of meteorological modeling are included. Examples of the use of the model as an evaluative planning tool and as a sensitivity analysis tool, examining sulfur dioxide standards, are given. A computer listing of the model is included.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

Increasing concern about the environmental effects of industrial practice has caused a revolution in the planning requirements of the electric power industry. The public is no longer satisfied simply to receive the power it demands. Through litigation, federal, state and local standards, and the pressures of public opinion, the public also requires that the power industry provide its product with minimal effect on the environment.

That the electric power industry should be one of the prime targets for those concerned about air pollution is understandable. It is a major and visible polluter, its fossil fueled plants producing 50% of the total national sulfur dioxide emissions and 25% of the total particulates annually. These enormous quantities combined with a growth rate which should quadruple the industry's size by the year 2000, mean that significant air pollution control must be exercised just to maintain today's environment.[28] Hopefully control may also improve the quality of the air, if not directly, then perhaps by encouraging the substitution of electricity for other sources of energy which cause more pollution. For a number of reasons then, the electric power industry is under increasing and immediate pressure, both justified and unjustified, to clean up the air pollution being caused by its operations.

This work is a description of the development of a planning tool for the electric power industry which will assist the power system planner in his efforts to produce power without unnecessary damage to the atmosphere. The air pollution characteristics and the costs of air pollution control are modeled for a combination of a new fossil fueled power plant, a site for the plant and a method of air pollution control. The remainder of this chapter discusses the planning problem in more detail after first covering some background material on air pollution standards and control alternatives.

AIR POLLUTION AND AIR POLLUTION STANDARDS

There are many different pollutants which result from the burning of a fossil fuel in a modern power plant. Sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter, carbon monoxide, carbon dioxide and hydrocarbons are the most significant. Of these, sulfur dioxide,[36] particulates[37] and nitrogen oxides are considered the most serious threats to health and property. The air pollution effects produced by the pollutants can be described as either global or local.

Global effects are those which occur over large areas and long periods of time, such as recent increases in sulfur dioxide concentrations over the oceans and polar areas. Global effects are most dependent on the total amounts of pollutants emitted into the atmosphere. Local effects, such as the all-too-familiar brown urban haze or soiling by particulates depend on the amounts of pollutants emitted and the manner in which the local meteorology and topography combine to disperse the pollutants. People generally notice the more rapidly changing local effects, although the dangers of global pollution are at least equally serious.

Adding to these effects are the background levels of pollutants. These ambient levels are due to both natural and man made causes, the differentiation being that man can control the man made portion of the background level. For example, a coastal site like Boston could have natural background levels of particulates from ocean salt spray, or the dust of distant fires, etc. Man made levels would result from incinerators, home heaters, cars or power plants.

The Environmental Protection Agency has established federal emission standards[30] applicable to power plants to control the global effects of emissions and hopefully to reduce the local effects as well. The emission standards specify the maximum emissions allowed per million Btu's of heat input to the boiler. Since poor plant design or weather conditions could produce dangerous local ground level concentrations of pollutants even if a plant is meeting the emission standards, the EPA has established standards for ground level concentrations.[31] These standards specify maximum average values for annual, twenty-four hour and three hour averaging periods.

These ground level air quality standards and the plant emission standards are listed in table I-1. States may adopt these federal standards or implement their own, provided the state standards are equally or more restrictive.

ABATEMENT ALTERNATIVES

As there are two types of air pollution effects, there are also two alternatives for controlling the air pollution produced by a plant.[9,10] The first is source control and is mainly concerned with the emissions or global effects. The second, atmospheric dispersion control, affects only ground level concentrations.

Source control, an essentially deterministic process, entails altering the plant design or operation so as to reduce emissions, resulting also in reduced ground level concentrations. Four available means for source control are fuel substitution, capacity reduction, process changes, and pollutant removal. Fuel substitution broadly includes fuel desulfurization, use of naturally nonpolluting fuels or switching to alternate generation like hydroelectric power. Capacity reduction would bring no improvement in terms of the present emission standards, but it would reduce ground level concentrations. Process changes would include redesign of the plant to reduce the production of pollutants. Pollutant removal requires that the polluted flue gases be treated and

TABLE I-1

FEDERAL EMISSION AND AIR QUALITY STANDARDS

Emission Standards (applicable to new or modified sources of more than 250 million Btu/hr heat input)

Particulates	Sulfur Dioxide
0.18 g/10^6 cal	1.4 g/10^6 cal (liquid fuel)
	2.2 g/10^6 cal (solid fuel)

Primary and Secondary Ambient Air Quality Standards

Primary standards are those deemed necessary, with a margin of safety, to protect public health.

Secondary standards are those deemed necessary to protect public welfare from known or anticipated adverse effects of pollutants.

	Primary Standards	
	Particulates	Sulfur Dioxide
Annual arithmetic mean	75 μg/m^3	80 μg/m^3
24 hr maximum (once/yr)	260 μg/m^3	365 μg/m^3
3 hr maximum (once/yr)	----	----

	Secondary Standards	
	Particulates	Sulfur Dioxide
Annual arithmetic mean	60 μg/m^3	60 μg/m^3
24 hr maximum (once/yr)	150 μg/m^3	260 μg/m^3
3 hr maximum (once/yr)		1300 μg/m^3

the pollutants removed or rendered harmless.

Nitrogen oxides, one of the three main pollutants produced by the normal power plant, can only be controlled by capacity reduction[38] or process changes, usually alterations in the boiler. No gas treatment method is now available and since the nitrogen oxides are formed primarily from atmospheric nitrogen, fuel substitution is ineffective.

Atmospheric dispersion control, relying on meteorological parameters, is stochastic in nature. It attempts to reduce the ground level concentrations resulting from a given emission rate by plant design and site choice. Good plant design of the stack height and the heat content of the stack gases can produce plume behavior which lessens the probability of high ground level concentrations. Site choice on the basis of topography and meteorology can influence the average behavior of the plume in a similarly favorable way. Consideration of known background levels, both natural and man made, can indicate whether a site can sustain the additional concentrations produced by the plant, and still meet the standards.

THE PLANNING PROBLEM

The system planner in the past developed his generation expansion strategies without including the possible costs and environmental tradeoffs of air pollution control methods. The strategies were developed on the basis of reliability and economic criteria, and after the number and size of the necessary plants were determined, the problem of siting the plants was addressed. The size and number of plants required in the future makes such a two-step procedure undesirable. Utilities no longer can be sure that an acceptable site can be found for each plant, because environmental constraints have eliminated many sites from consideration.

One goal of this work is to provide a tool to answer the question, "What is the feasibility of a given combination of plant-site-abatement equipment (hereafter called a PSA alternative)?" That is, if a particular type of new fossil fueled plant is specified, along with some means of air pollution abatement, and it is placed on a site type of known topography, meteorology and background concentrations, will the combination meet the emission and air quality standards? Such knowledge can indicate to the planner which PSA alternatives he can consider feasible in his planning strategies. If the plant is environmentally feasible, the economic feasibility of the plant and abatement equipment is determined in terms of the investment and operating costs.

This particular approach to the feasibility question is chosen in order to provide support for a generation expansion planning model which is described in appendix B. The combination of the generation expansion planning model and the evaluative model which results from this work can be used by the system planner to include air environmental constraints in his planning strategies.

A second goal of this work is to provide a tool to answer the question, "What are the sensitivities of pollution and costs to standards changes?" That is, if a plant were forced to meet different levels of pollution standards, what trade-offs would develop between actual pollution levels and the costs required to meet those levels? Clearly, the answer to the second question could affect the constraints applied in the first, and change drastically the system planner's options.

The tool is the previously mentioned model of the air pollution characteristics and abatement economic characteristics of a given PSA combination. The two goals require that the model be able to perform two broad functions:

1) Determine if a PSA combination meets the specified emission and air quality standards.
2) Evaluate the economic and environmental costs of the applied air pollution control method.

Chapter II gives an overview of the model structure and considers two examples of the application of the model. Chapters III, IV and V explain the detailed model structure, while chapter VI gives conclusions and recommendations for further research. Supporting appendices and references complete this work.

CHAPTER II

MODEL OVERVIEW AND EXAMPLES

The model is designed to determine the air environmental feasibility and the abatement economics, resource requirements and plant effects for a prespecified plant-site-abatement (PSA) alternative. Such an alternative consists of a power plant type, a site type for the plant, and a means of air pollution control.

This chapter first discusses the assumptions made about the power plant and its site, and about the abatement method and its economics. The operating logic of the model is then given as an introduction to two sample applications of the model.

MODEL ASSUMPTIONS

The major assumptions made about the model are as follows:

General

1. Prespecified PSA alternatives are evaluated.
2. Only sulfur dioxide and particulates are considered.
3. The model is designed to consider only steam generating plants.

Plant

1. Plant performance is parameterized.
2. The stack is not considered part of the plant.

Site

1. Six alternatives of type and background are considered.
2. Representative meteorological data applies to all sites of the same alternative.

Abatement Method

1. Four types are considered.
2. Abatement performance is parameterized.
3. Stack heights are decided by the model.

Economics

1. Five costs are calculated.
2. Abatement economics are parameterized.

GENERAL ASSUMPTIONS

The model evaluates combinations of plant type, site type and abatement method. It makes its one optimizing choice when it decides plant stack height as the smallest value (of a set of values) which will enable the plant to be air environmentally feasible, i.e. meet the air pollution standards. It does not attempt to determine the best site or cheapest abatement method. These decisions are made by the system planner using the model's results.

Although nitrogen oxides are one of the three main power plant pollutants, the model does not consider them. This is because the only means of nitrogen oxide control are capacity reduction or boiler design changes. Since nitrogen oxides are inert and form from atmospheric nitrogen in the boiler flame area, no flue gas treatment method or fuel substitution will significantly reduce their emissions. Changing boiler design would be a complicated task and could well make the model's results less reliable. It was decided to assume that all new boilers such as this model is evaluating would come with adequate nitrogen oxides controls. If it were desired to evaluate nitrogen oxides, the boiler and meteorological models are applicable, and only relatively few program changes would be needed.

The model is designed to evaluate fossil fueled steam generating plants since these are the most common plants, carry the most load, and produce the most emissions. An adaptation to include gas turbines is included in appendix B. Although fossil plants can be base loaded, intermediate or peaking plants in practice, the model evaluates them all at 100% capacity factor to get worst case meteorological comparisons.

Abatement parameters can adjust for the lower operating cost of peaking operation for example, through a quantity called "stream time". This is the actual hours of operation for the abatement equipment. Although the plant is assumed to operate at 100% capacity continuously, "stream time" is the length of time in hours per year for which abatement costs are evaluated.

PLANT ASSUMPTIONS

The plant is considered in terms of the air pollution characteristics only, so most electrical and mechanical aspects are ignored by the model. The boiler operation is emphasized. Since the stack height is designed by the model for air pollution control purposes, it is not considered part of the prespecified plant and its cost will be included in the abatement costs.

The following parameters are assumed to be determined by factors other than air pollution control, and are used to represent the air pollution aspects of the prespecified plant and its fuel.

1. Plant type
2. Plant size (MW)
3. Fuel type
4. Fuel sulfur content
5. Fuel ash content
6. Fuel heat equivalent
7. Boiler gas flow
8. Boiler exit gas temperature
9. Boiler heat input
10. Boiler efficiency
11. Stack gas sulfur dioxide content (spare)
12. Stack gas particulate content (spare)

Plant type specifies fossil base loaded, peaking or intermediate for information purposes and possible abatement economics use. At present all three types are treated the same. Plant combustion method is also given if coal is burned since different combustion methods affect ash emissions. Plant size in MW is the plant's maximum capacity.

Fuel type, either coal, oil or gas is accompanied by fuel sulfur and ash contents, specified as "high", "medium" or "low". Numerical values are assigned for these in the model. The heat equivalent of the fuel must be in units compatible with the emission factors used, Btu/ton for coal, Btu/10^3 gal for oil and Btu/10^6 ft^3 for gas.

The boiler gas flow is the gas volume in ACFM leaving the boiler at the boiler-exit gas temperature. These determine fan power and abatement train size. Boiler heat input in Btu/hr and boiler efficiency in percent determine fuel use and plume rise. The last two parameters originally were to be used to determine abatement efficiencies while the model was used in connection with the generation expansion program of appendix B. Their use has now been deleted, but the parameters remain as spares. Their values in no way affect model operation at present.

SITE ASSUMPTIONS

It would be impossible to find two sites which exhibit identical meteorological characteristics with regards to atmospheric dispersion of pollutants and pollutant background levels. To attempt to examine the air pollution characteristics of all possible sites which are otherwise feasible is equally impossible. Thus, a level of aggregation was assumed so that all possible sites are classed into site types by topography, meteorology and background levels.

Six alternatives result: urban coastal, rural coastal, urban valley, rural valley, urban plain and rural plain. The alternative to be evaluated is prespecified and representative meteorological data are introduced into the model.

Although representative data are employed, a main assumption is that if a plant is air environmentally feasible or infeasible at the representative site, it will be the same at all the sites in that class. While exceptions are sure to exist, model results should show trends helpful in ultimate site planning.

ABATEMENT METHOD ASSUMPTIONS

The height of the stack is the controllable design factor in all the abatement methods. Otherwise, each abatement method is parameterized before the model begins, to reflect its operation and economics. Four abatement methods are considered by the model:

1) Wet limestone scrubbing
2) Catalytic oxidation
3) Magnesium oxide scrubbing
4) Tall stacks (and precipitators)

The methods are parameterized because of the uncertainty and lack of operating experience surrounding their performance data. The first three are chosen as the most promising methods at this date,[11] and the fourth, with no SO_2 control, is included for comparison as a continuation of past plant construction practices. The fourth method also would be useful to investigate the effects of the failure of the first three methods to become commercially acceptable. The model assumes that the parameters available for each method can represent the abatement effectiveness and operations adequately.

One factor of abatement operation which is not parameterized, or dealt with in this model is reliability of operation. This factor may eventually prove to be the most important parameter. Since it is so undesirable to have a power plant unavailable unexpectedly, the system planner will be concerned about whether failure of part of the abatement process necessitates shutting down the whole plant. If the abatement devices of the model prove to be unreliable with frequent outages, and this affects overall plant reliability, then they may not gain industry acceptance.

Reliability was not included in the model because it is basically a system level problem and the model works with individual plants. Reliability concerns will ultimately be handled at the level of the generation expansion planning model.

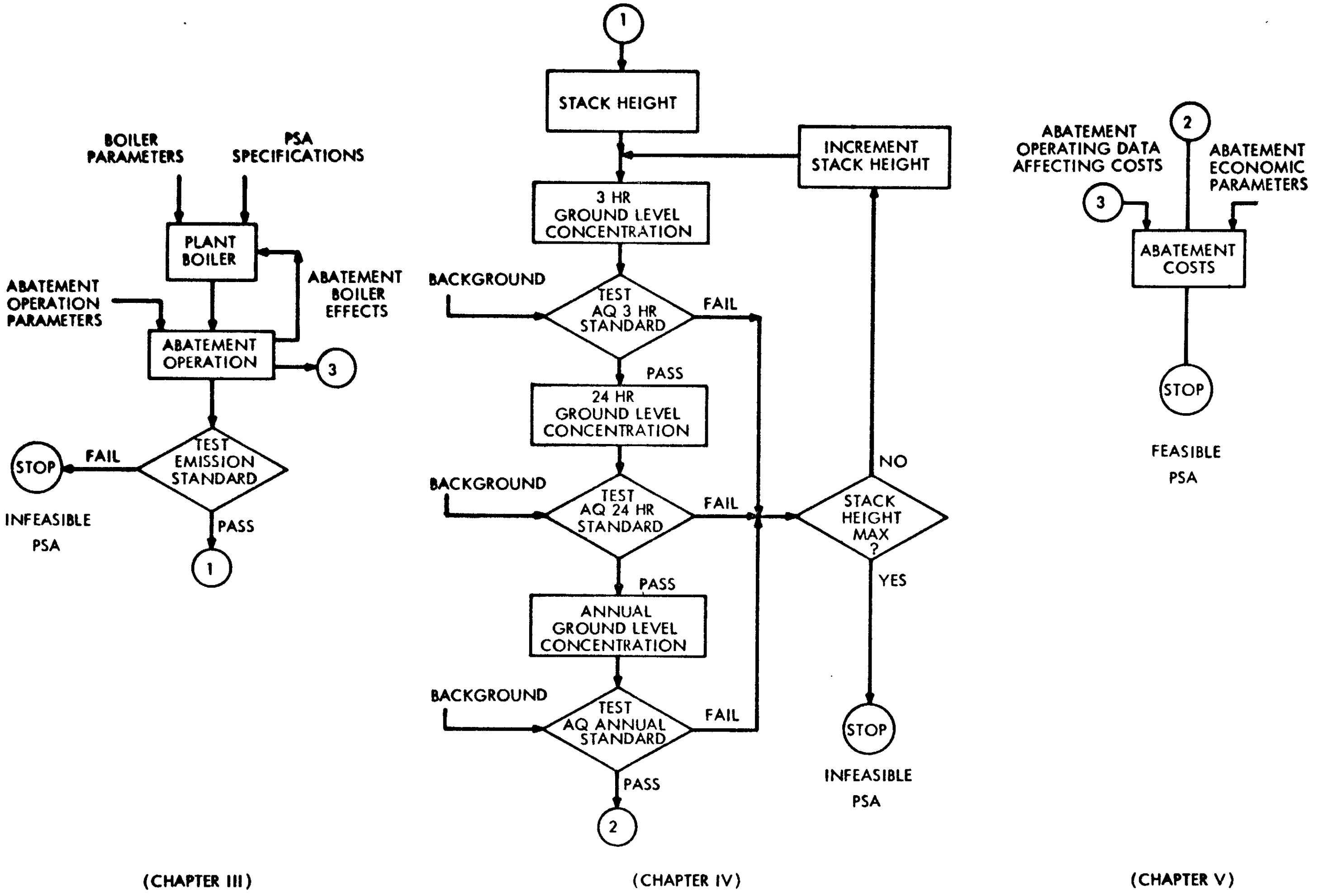
ECONOMICS ASSUMPTIONS

Five costs are determined for the stack height and abatement method finally used. These are the capital cost of the stack and equipment, the fixed operating costs, the variable operating costs, and two "resource costs", the water and land consumption of the plant abatement method. The power consumption and boiler efficiency change due to air pollution control also are determined.

As with abatement operations, the parametric representation is chosen because of the present uncertainty in costs, and it is assumed that the parameters chosen adequately represent the abatement costs.

MODEL OPERATING LOGIC

Figure 2.1 indicates the procedures used in evaluating any prespecified PSA combination. The diagram represents the decision logic used to deal with a fossil fueled steam generating plant. Gas turbines, mentioned in appendix B, would be handled in a similar way with different numerical values in the model. The diagram is self explanatory. The three indicated segments, covering boiler and abatement operation, meteorological modeling and abatement economics are treated in detail in the next three chapters.



Model Operating Logic

Figure 2.1.

MODEL EXAMPLE I

This example is intended to demonstrate to the reader the evaluative capability of the model, emphasizing two things: the meteorological results and the abatement process information produced. It should be noted that the feasibility decision and the five cost quantities, as well as power consumption and boiler efficiency change, are automatically returned to the generation expansion planning program whether or not the model results are printed and that only these quantities are returned. The results are printed here via a print logic control variable to familiarize the reader with the information available.

A 250 MW coal fired plant is evaluated at a valley site for each of the four abatement processes. In order to ensure complete printouts, the model logic is overridden during the emissions standards testing. As can be seen on the next four pages, this logic override causes the wet limestone and tall stacks evaluations to printout that the PSA alternative both fails and passes the emissions test. The numerical values show that the plant actually does fail.

These outputs are intended to be self-explanatory and the reader will profit most by examining the different processes in order to make comparisons between methods. A few interesting results are immediately apparent. In general, the site's dispersion characteristics are good as all the ground level

```
                                                  AIR POLLUTION COST CONTROL PROGRAM
PLANT ID CODE     FRGX   CHMX     250   1972  XVUX   XXXX   WLNX

PLANT TYPE     = FRG   SITE TYPE     = V     FUEL TYPE        = C     SO2 EMISSION FACTOR =    38.0  SO2EMB =     2022. G/S,
PLANT SIZE     =  250  URBANIZATION = U     SULFUR CONTENT =  4.5  PARTICULATE E.F.     =    16.0  PEMB   =     4006. G/S
PLANT VINTAGE = 1972  ABATEMENT     = WL    ASH CONTENT      = 15.0  BYPRODUCT CREDITS    =     0.0  AVFUEL =       94. UPH

SYSTEM FAILS TO MEET STACK EMISSION STANDARDS
........................................................................................................................
     SO2                       SO2                           PARTICULATES                    PARTICULATES
 STACK EMISSIONS   =     1.28 STANDARD=     2.20 G/MCAL     STACK EMISSIONS    =     0.25 STANDARD=     0.18G/MCAL
........................................................................................................................

SYSTEM MEETS ALL AIR POLLUTION STANDARDS
      SO2                      SO2                           PARTICULATES                    PARTICULATES
 STACK EMISSIONS   =      1.28 STANDARD=     2.20 G/MCAL     STACK EMISSIONS    =     0.25 STANDARD=     0.18 G/MCAL
 3 HR GL MAX CONC  =   291.65 STANDARD= 1300.00 MMG/CU.M    3 HR GL MAX CONC   =    57.78 STANDARD=   500.00 MMG/CU.M
 24HR GL MAX CONC  =     90.83 STANDARD=  260.00 MMG/CU.M    24HR GL MAX CONC   =    18.00 STANDARD=   150.00 MMG/CU.M
 ANNUAL GL MAX CONC=    34.00 STANDARD=    60.00 MMG/CU.M    ANNUAL GL MAX CONC=     6.74 STANDARD=    60.00 MMG/CU.M
 LIMITED MIXING DEPTH=  197. M, AT   1790. M; STACK HT= 125.M; SO2 BGRND=  10.000MMG/CU.M PART BGRND=  10.000MMG/CU.M
 ANNUAL MAX GL CONC IN SE  DIRECTION AT    7000.METERS DOWNWIND      STACK HEAT EMISSION  =   143870096. BTU/HR
 VALLEY DEPTH IS     100.M

                                                  WET LIMESTONE SCRUBBING
........................................................................................................................
                                                  ANNUAL OPERATING DATA
     PLANT SIZE (MW)              250                                              STACK CAPITAL COSTS     $   331250.
     TRAIN SIZE (ACFM)         400000.                                          EQUIPMENT CAPITAL COST     $  6750000.
     GAS FLOW (ACFM)           585805.                                 FIXED CAPITAL INVESTMENT(FCI)     $  7081250.
     NUMBER OF TRAINS              2.                                              STREAM TIME (HR/YR)          8760.
........................................................................................................................

FIXED OPERATING COSTS                                                      ....$/YR..     SYSTEM DATA

  1. OPERATING LABOR ( 2. MEN/SHIFT @ $  5.00/HR)                          87600. XX SO2 REMOVAL EFF         90.0 %
  2. SUPERVISION  15.0% OF ITEM 1                                          13140. XX PART REMOVAL EFF        99.0 %
  3. MAINTENANCE LABOR AND MATERIALS   4.0% OF FCI                        283250. XX TOTAL ELCTRIC POWER   2634.1 KW
  4. PLANT SUPPLIES  15.0% OF ITEM 3                                       42487. XX FLYASH DISP AREA        14.6 A
  5. PAYROLL OVERHEAD  20.0% OF (1+2)                                      20148. XX PRESSURE DROP           23.0 IN
  6. PLANT OVERHEAD  50.0% OF (1+2+3+4)                                   213239. XX STACK GAS TEMP         225.0 F
  7. CAPITAL CHARGES   18.0% OF FCI                                      1274624. XX PUMP ELEC POWER       2387.3 KW
  8. TOTAL FIXED OPERATING COST................................... $  1934487. XX
                                                                                   XX
........................................................................................................................
........................................................................................................................

VARIABLE OPERATING COSTS                                                           XX CACO3 IN LIMESTONE       90.0 %
                                                                                   XX CALC HEAT/T LIMESTONE     2.0 BTU
  1. WATER CONSUMPTION                 42.3 GPS @$  0.20/MGAL                 298. XX STOICHIOMETRIC RATE     110.0 %
  2. LIMESTONE                         15.3 TPH @$  2.00/TON               268189. XX SOLIDS DISP AREA         27.6 A
  3. DISPOSAL OF FLYASH                11.1 TPH @$  0.40/TON                39026. XX BOILER EFF. CHANGE       -1.4 %
  4. DISPOSAL OF PROCESS SOLIDS        15.8 TPH @$  0.50/TON                69071. XX CAOHOH PRODUCTION         0.8 TPH
  5. CREDITS                                                       (           0.)XX
  6. ELECTRICITY COST     23074448. KWH       @   6.75MILLS/KWH            155753. XX
  7. TOTAL VARIABLE OPERATING COSTS................................ $    532336. XX
  8. CAPACITY FACTOR ADJUSTED VARIABLE OPERATING COSTS                        5323. XX
........................................................................................................................
   90.00000    99.00000   225.00000  8760.00000     0.40000     0.01500
    2.00000  1600.00000    27.00000     0.40000     0.0         4.00000
    0.05000   -10.00000   800.00000    18.00000     5.00000    15.00000
   15.00000    20.00000    50.00000     6.75000
   90.00000   110.00000     2.00000     0.02000 31000.0000  50000.0000
   23.00000     2.00000     0.50000     0.20000    25.00000
```

```
                                   AIR POLLUTION COST CONTROL PROGRAM
PLANT IC CODE     FBGX   CHMX     250   1972  XVUX    XXXX    COCX

PLANT TYPE    = FBG   SITE TYPE     = V      FUEL TYPE       = C     SO2 EMISSION FACTOR =   38.0  SO2EMB =      2022. G/S,
PLANT SIZF    =  250  URBANIZATION = U       SULFUR CONTENT =  4.5   PARTICULATE E.F.    =   16.0  PEMB   =      2837. G/S
PLANT VINTAGE = 1972  ABATEMENT     = CO     ASH CONTENT     = 15.0  BYPRODUCT CREDITS   =    1.0  AVFUEL =        94. UPH
...........................................................................................................................

SYSTEM MEETS ALL AIR POLLUTION STANDARDS
     SO2                          SO2                               PARTICULATES                  PARTICULATES
STACK EMISSIONS    =     1.28 STANDARD=    2.20 G/MCAL      STACK EMISSIONS    =      0.09 STANDARD=     0.18 G/MCAL
3 HR GL MAX CONC   =   270.30 STANDARD= 1300.00 MMG/CU.M    3 HR GL MAX CONC   =     18.97 STANDARD=   500.00 MMG/CU.M
24HR GL MAX CONC   =    84.18 STANDARD=  260.00 MMG/CU.M    24HR GL MAX CONC   =      5.91 STANDARD=   150.00 MMG/CU.M
ANNUAL GL MAX CONC=     33.35 STANDARD=   60.00 MMG/CU.M    ANNUAL GL MAX CONC=       2.34 STANDARD=    60.00 MMG/CU.M
LIMITED MIXING DEPTH=  205. M, AT    1856. M; STACK HT= 125.M; SO2 BGRND=  10.000MMG/CU.M PART BGRND=  10.000MMG/CU.M
ANNUAL MAX GL CONC IN SE  DIRECTION AT     7000.METERS DOWNWIND       STACK HEAT EMISSION  =     170913392. BTU/HR
VALLEY DEPTH IS     100.M

                                          CATALYTIC OXIDATION
...........................................................................................................................
                                         ANNUAL OPERATING DATA
    PLANT SIZE (MW)               250                                        STACK CAPITAL COSTS      $   331250.
    TRAIN SIZE (ACFM)          500000.                                  EQUIPMENT CAPITAL COST        $ 11250000.
    GAS FLOW (ACFM)            607203.                         FIXED CAPITAL INVESTMENT(FCI)          $ 11581250.
    NUMBER OF TRAINS                2.                                       STREAM TIME (HR/YR)            8760.
...........................................................................................................................

FIXED OPERATING COSTS                                                           ....$/YR..     SYSTEM DATA

  1. OPERATING LABOR ( 4. MEN/SHIFT @ $  5.00/HR)                                175200. XX SO2 REMOVAL EFF         90.0 %
  2. SUPERVISION  15.0% OF ITEM 1                                                 26280. XX PART REMOVAL EFF        99.5 %
  3. MAINTENANCE LABOR AND MATERIALS   4.5% OF FCI                               521156. XX TOTAL ELCTRIC POWER   3982.7 KW
  4. PLANT SUPPLIES   15.0% OF ITEM 3                                             78173. XX FLYASH DISP AREA        14.7 A
  5. PAYROLL OVERHEAD  20.0% OF (1+2)                                             40296. XX PRESSURE DROP           33.5 IN
  6. PLANT OVERHEAD   50.0% OF (1+2+3+4)                                         400405. XX STACK GAS TEMP         250.0 F
  7. CAPITAL CHARGES   18.0% OF FCI                                             2084624. XX PUMP ELEC POWER        537.1 KW
  8. TOTAL FIXED OPERATING COST......................................... $     3326134. XX
                                                                                         XX
...........................................................................................................................
...........................................................................................................................

VARIABLE OPERATING COSTS                                                                 XX CATALYST GAS TEMP     900.0 F
                                                                                         XX CATALYST LOADING     6000.0 CU.FT
  1. WATER CONSUMPTION          1.7 GPS          @ $  0.20/MGAL                      11. XX CATALYST ATTRITION     10.0 %
  2. CATALYST MAKEUP        600.0 CU.FT.         @ $ 38.25/CU.FT.                 22950. XX BOILER EFF CHANGE       0.0 %
  3. FLYASH DISPOSAL         11.2 TPH            @ $  0.40/TON                    39223. XX
  4. COOLING WATER          150.0 LB/HR          @ $  0.03/MGAL                     142. XX
  5. CREDITS                 14.2 TPH H2SO4      @ $  4.00/TON 77.7% ACID  (    498160.)XX
  6. ELECTRICITY COST      34888555. KWH         @    6.75MILLS/KWH              235498. XX
  7. TOTAL VARIABLE OPERATING COSTS................................... $   -200478. XX
  8. CAPACITY FACTOR ADJUSTED VARIABLE OPERATING COSTS                          -2005. XX
...........................................................................................................................
   90.00000     99.50000    250.00000  8760.00000     0.50000      0.01500
    4.00000    360.00000     45.00000     0.40000     4.00000      4.50000
    0.05000    -10.00000    800.00000    18.00000     5.00000     15.00000
   15.00000     20.00000     50.00000     6.75000
  900.00000   3000.00000     10.00000 40000.0000    150.00000      3.00000
   33.50000     38.25000      0.20000     0.03000
```

```
                                   AIR POLLUTION COST CONTROL PROGRAM
PLANT ID CODE     FBGX   CHMX     250   1972  XVUX   XXXX   MGCX

PLANT TYPE     = FBG   SITE TYPE     = V     FUEL TYPE        = C     SO2 EMISSION FACTOR =   38.0  SO2EMR =     2022. G/S,
PLANT SIZE     =  250  URBANIZATION = U     SULFUR CONTENT =  4.5  PARTICULATE E.F.    =   16.0  PEMR   =     2837. G/S
PLANT VINTAGE = 1972  ABATEMENT     = MG    ASH CONTENT      = 15.0  BYPRODUCT CREDITS   =    1.0  AVFUEL =       94. UPH
...............................................................................................................................

SYSTEM MEFTS ALL AIR POLLUTION STANDARDS
      SO2                         SO2                              PARTICULATES                  PARTICULATES
 STACK EMISSIONS    =      1.28 STANDARD=     2.20 G/MCAL      STACK EMISSIONS     =      0.09 STANDARD=     0.18 G/MCAL
 3 HR GL MAX CONC   =   267.98 STANDARD= 1300.00 MMG/CU.M     3 HR GL MAX CONC    =     19.40 STANDARD=   500.00 MMG/CU.M
 24HR GL MAX CONC   =    83.46 STANDARD=   260.00 MMG/CU.M     24HR GL MAX CONC    =      6.04 STANDARD=   150.00 MMG/CU.M
 ANNUAL GL MAX CONC=     33.28 STANDARD=    60.00 MMG/CU.M     ANNUAL GL MAX CONC=        2.41 STANDARD=    60.00 MMG/CU.M
 LIMITED MIXING DEPTH=  206. M, AT    1864. M; STACK HT= 125.M; SO2 BGRND=  10.000MMG/CU.M PART BGRND=  10.000MMG/CU.M
 ANNUAL MAX GL CONC IN SE  DIRECTION AT    7000.METERS DOWNWIND      STACK HEAT EMISSION  =    174262288. BTU/HR
 VALLEY DEPTH IS     100.M

                                        MAGNESIUM OXIDE SCRUBBING
...............................................................................................................................
                                          ANNUAL OPERATING DATA
    PLANT SIZE (MW)                  250                                        STACK CAPITAL COSTS     $   331250.
    TRAIN SIZE (ACFM)             400000.                                   EQUIPMENT CAPITAL COST     $  8650000.
    GAS FLOW (ACFM)               585805.                              FIXED CAPITAL INVESTMENT(FCI)   $  8981250.
    NUMBER OF TRAINS                  2.                                        STREAM TIME (HR/YR)          8760.
...............................................................................................................................

FIXED OPERATING COSTS                                                   ....$/YR..     SYSTEM DATA

  1. OPERATING LABOR ( 4. MEN/SHIFT a $  5.00/HR)                        175200. XX SO2 REMOVAL EFF          90.0 %
  2. SUPERVISION  15.0% OF ITEM 1                                         26280. XX PART REMOVAL EFF         99.5 %
  3. MAINTENANCE LABOR AND MATERIALS   4.0% OF FCI                       359250. XX TOTAL ELCTRIC POWER    2412.0 KW
  4. PLANT SUPPLIES  15.0% OF ITEM 3                                      53887. XX FLYASH DISP AREA         14.7 A
  5. PAYROLL OVERHEAD  20.0% OF (1+2)                                     40296. XX PRFSSURE DROP            21.0 IN
  6. PLANT OVERHEAD  50.0% OF (1+2+3+4)                                  307309. XX STACK GAS TEMP          225.0 F
  7. CAPITAL CHARGES   18.0% OF FCI                                     1616624. XX PUMP ELFC POWER        1223.5 KW
  8. TOTAL FIXED OPERATING COST.................................... $  2578845. XX
                                                                                 XX
...............................................................................................................................
...............................................................................................................................

VARIABLE OPERATING COSTS                                                         XX ACID PLANT FCI           2.0 M$
                                                                                 XX PLANT SHARE OF FCI      20.0 %
  1. WATER CONSUMPTION      18.8 GPS          a $  0.20/MGAL                  119. XX BOILER EFF CHANGE        0.0 %
  2. MGO MAKEUP              0.0 TPH          a $ 40.00/TON              4204800. XX DRYER ELEC POWER         7.0 MW
  3. DRYER FUEL             50.7 MBTU/HR      a $  0.40/MBTU              177490. XX DRYER ASH COLL EFF      90.0 %
  4. FLYASH DISPOSAL        11.2 TPH          a $  0.40/TON                39223. XX DRYER STACK HEAT        60.0 %
  5. ACID PLANT COSTS       11.8 TPH DRYCAKE a $  0.20/TON   30.0% SHARE    6190. XX INITIAL MGO LOADING   110.0 TON
  6. ELECTRICITY COST     21129280. KWH       a    6.75MILLS/KWH          142623. XX
  7. CREDITS                11.8 TPH DRYCAKE a $  0.80/TON           (    82533.)XX SO2 TO MGSO4             3.0 %
  8. TOTAL VARIABLE OPERATING COSTS................................ $  4487908. XX SO2 TO MGSO3.3H2O       20.0 %
  9. CAPACITY FACTOR ADJUSTED VARIABLE OPERATING COSTS                     44879. XX
...............................................................................................................................
    90.00000    99.50000   225.00000  8760.00000     0.40000     0.01500
     4.00000   820.00000    33.00000     0.40000     0.80000     4.00000
     0.05000   -10.00000   800.00000    18.00000     5.00000    15.00000
    15.00000    20.00000    50.00000     6.75000
    10.00000    20.00000     3.00000   110.00000     0.80000 40000.0000
     2.00000    60.00000     0.40000     3.00000    90.00000     7.00000
 31000.0000     30.00000    20.00000    40.00000    21.00000     0.20000
     2.00000     0.20000
```

```
                                       AIR POLLUTION COST CONTROL PROGRAM
PLANT ID CODE     FBGX   CHMX      250     1972  XVUX   XXXX   TSNX

PLANT TYPE    = FBG   SITE TYPE    = V      FUEL TYPE      = C     SO2 EMISSION FACTOR =    38.0  SO2EMB =     2022. G/S,
PLANT SIZE    =  250  URBANIZATION = U      SULFUR CONTENT =  4.5  PARTICULATE E.F.    =    16.0  PEMB   =     2837. G/S
PLANT VINTAGE = 1972  ABATEMENT    = TS     ASH CONTENT    = 15.0  BYPRODUCT CREDITS   =     0.0  AVFUEL =       94. UPH

SYSTEM FAILS TO MEET STACK EMISSION STANDARDS
.......................................................................................................................
      SO2                   SO2                          PARTICULATES                 PARTICULATES
 STACK EMISSIONS   =   12.84 STANDARD=    2.20 G/MCAL     STACK EMISSIONS   =    0.09 STANDARD=    0.18G/MCAL
.......................................................................................................................

SYSTEM MEETS ALL AIR POLLUTION STANDARDS
      SO2                   SO2                          PARTICULATES                 PARTICULATES
 STACK EMISSIONS   =   12.84 STANDARD=     2.20 G/MCAL    STACK EMISSIONS   =     0.09 STANDARD=     0.18 G/MCAL
 3 HR GL MAX CONC  =  745.70 STANDARD= 1300.00 MMG/CU.M   3 HR GL MAX CONC  =     5.23 STANDARD=  500.00 MMG/CU.M
 24HR GL MAX CONC  =  232.24 STANDARD=   260.00 MMG/CU.M  24HR GL MAX CONC  =     1.63 STANDARD=  150.00 MMG/CU.M
 ANNUAL GL MAX CONC=    40.91 STANDARD=   60.00 MMG/CU.M  ANNUAL GL MAX CONC=     0.29 STANDARD=   60.00 MMG/CU.M
 LIMITED MIXING DEPTH=  402. M, AT    3434. M; STACK HT= 275.M; SO2 BGRND= 10.000MMG/CU.M PART BGRND=  10.000MMG/CU.M
 ANNUAL MAX GL CONC IN E   DIRECTION AT  70000.METERS DOWNWIND     STACK HEAT EMISSION  =   224999904. BTU/HR
 VALLEY DEPTH IS     100.M

                                        TALL STACK WITH PRECIPITATOR
.......................................................................................................................
                                          ANNUAL OPERATING DATA
     PLANT SIZE (MW)              250                                  STACK CAPITAL COSTS     $  1831250.
     TRAIN SIZE (ACFM)         250000.                              EQUIPMENT CAPITAL COST     $   500000.
     GAS FLOW (ACFM)           650000.                        FIXED CAPITAL INVESTMENT(FCI)    $  2331250.
     NUMBER OF TRAINS               3.                                STREAM TIME (HR/YR)            8760.
.......................................................................................................................

FIXED OPERATING COSTS                                                  ....$/YR..    SYSTEM DATA

  1. OPERATING LABOR ( 0. MEN/SHIFT @ $  5.00/HR)                            0. XX SO2 REMOVAL EFF          0.0 %
  2. SUPERVISION  15.0% OF ITEM 1                                            0. XX PART REMOVAL EFF        99.5 %
  3. MAINTENANCE LABOR AND MATERIALS   0.8% OF FCI                       18650. XX TOTAL ELCTRIC POWER    514.3 KW
  4. PLANT SUPPLIES  15.0% OF ITEM 3                                      2798. XX FLYASH DISP AREA        14.7 A
  5. PAYROLL OVERHEAD  20.0% OF (1+2)                                        0. XX PRESSURE DROP            4.0 IN
  6. PLANT OVERHEAD  50.0% OF (1+2+3+4)                                  10724. XX STACK GAS TEMP         300.0 F
  7. CAPITAL CHARGES   18.0% OF FCI                                     419625. XX PUMP ELEC POWER          0.0 KW
  8. TOTAL FIXED OPERATING COST.................................... $  451796. XX
                                                                              XX
.......................................................................................................................
.......................................................................................................................

VARIABLE OPERATING COSTS                                                      XX PRECIPITATOR POWER       2.0 KW
                                                                              XX BOILER EFF CHANGE        0.0 %
  1. CREDITS                                                      (          0.)XX
  2. FLYASH DISPOSAL        11.2 TPH          @ $  0.40/TON              39223. XX
  3. ELECTRICITY COST      4505264. KWH       @    6.75MILLS/KWH         30411. XX
  4. TOTAL VARIABLE OPERATING COSTS................................ $    69633. XX
  5. CAPACITY FACTOR ADJUSTED VARIABLE OPERATING COSTS                     696. XX
.......................................................................................................................
    0.0         99.50000   300.00000  8760.00000     0.25000     0.01500
    0.0          0.0         2.00000     0.40000     0.0         0.80000
    0.05000    -10.00000   800.00000    18.00000     5.00000    15.00000
   15.00000     20.00000    50.00000     6.75000
    2.00000      4.00000
```

standards are met. It must be emphasized that the sum of the pollution levels and the background levels must not exceed the standards. Plume rise is good, as indicated by the limited mixing depth value.

Wet limestone suffers from the excess particulate loading of limestone injection as shown by boiler particulate emissions. A lower particulate removal efficiency than the other methods also contributes to the plant's failure to meet emission standards. Catalytic oxidation is the only process to make an operating profit through its sale of acid. But its high capital investment requirements, by increasing fixed costs, nullify the cost advantage due to byproducts.

Magnesium oxide scrubbing in this run was placed at a disadvantage by a high magnesium oxide makeup rate. The makeup costs are over 90% of the total variable operating costs. But even without makeup costs, byproduct credits would not offset operating expenses. The tall stack results point out the method's basic weakness as the sulfur dioxide emission limits are not met. By increasing the stack height, the model was able to meet all the air quality standards, with the twenty-four hour standard apparently being the last one met. Of course, this method has the lowest costs.

Following each abatement method output is a listing of the abatement parameter values used in the evaluation. These are not titled, but represent the exact data input by the model according to the form used in appendix D. Each line of data is one input record, as it appears in the parameter data file (file 18) or on the input cards.

MODEL EXAMPLE II

This model is intended to demonstrate to the reader the sensitivity analysis capability of the model, emphasizing its application to sulfur dioxide air quality standards. From the first model example, it appeared that of the three hour and twenty-four hour standards, the latter was tighter and would be more critical in determining plant feasibility. This second model example examines the economic effects of variations in these two standards.

The second model example evaluates a plant type similar to that of the first model, a coal fired plant at a valley site, but uses only one abatement method, catalytic oxidation. This is done to prevent the economic effects of different abatement methods from confusing the standards' effects. The same process is repeated, using plant sizes of 1000 MW, 200 MW, and 100 MW, to see if the standards influence different plant sizes differently. The results, in terms of effects on the capital required for abatement, are shown in figures 2.2 and 2.3.

The figures demonstrate a definite growth in capital as the standards are tightened. There are two factors reflected in the shape of the curves. The flat portion represents the initial capital outlay for the abatement trains. This amount

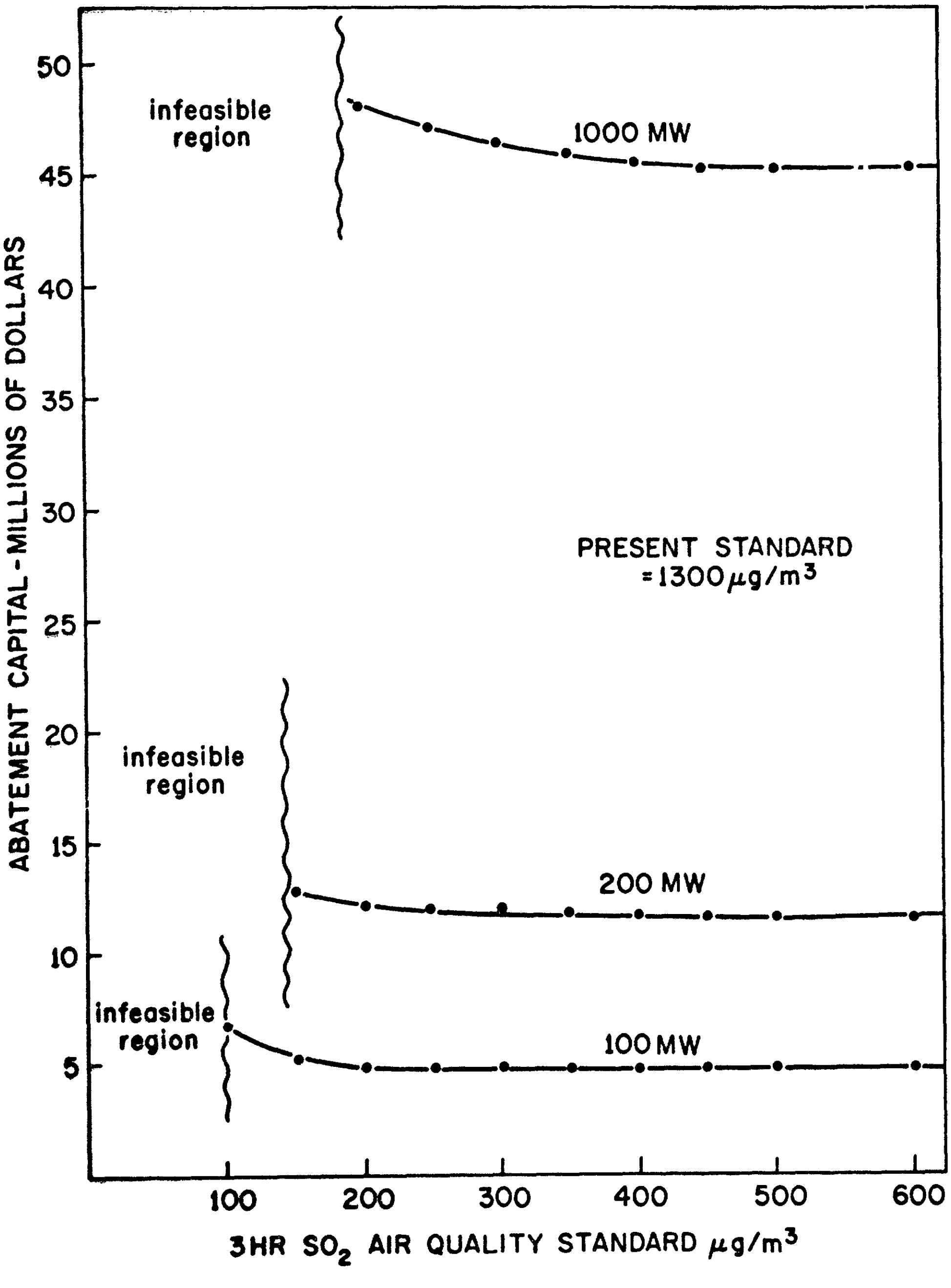

ABATEMENT CAPITAL - MILLIONS OF DOLLARS
5
10
15
20
25
30
35
40
45
50
100
200
300
400
500
600
3HR SO2 AIR QUALITY STANDARD μg/m3
infeasible region
infeasible region
infeasible region
1000 MW
200 MW
100 MW
PRESENT STANDARD =1300μg/m3

Figure 2.2.

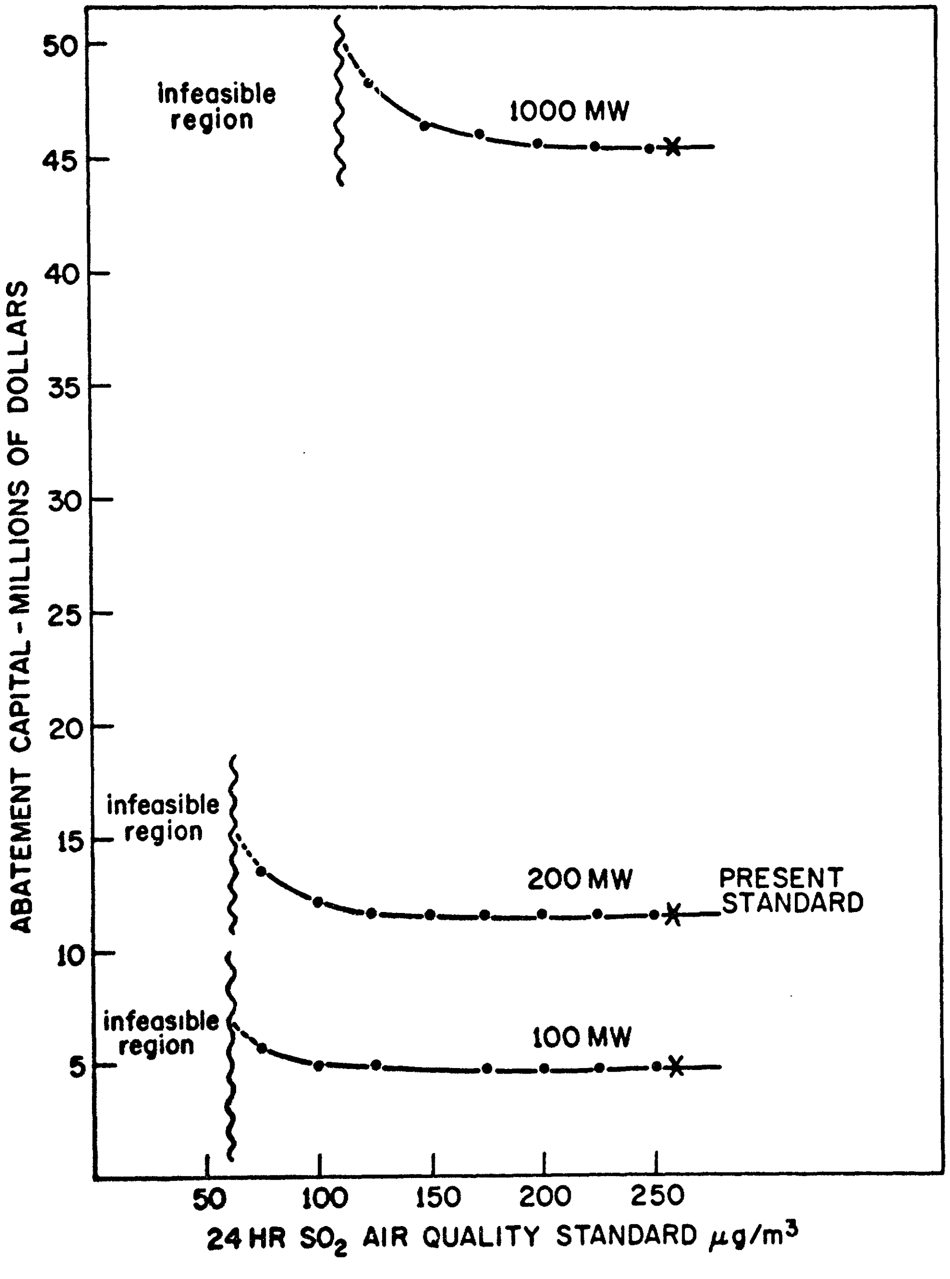

ABATEMENT CAPITAL - MILLIONS OF DOLLARS
50
45
40
35
30
25
20
15
10
5
infeasible region
1000 MW
infeasible region
200 MW
PRESENT STANDARD
infeasible region
100 MW
50
100
150
200
250
24 HR SO2 AIR QUALITY STANDARD μg/m3

Figure 2.3.

depends on plant size and the cost of the abatement equipment. The capital required for the minimum necessary stack height of 100 m is also included. The increasing portion of the curve represents the model's constructing added stack height in an effort to meet the tightening standards. A background of 50 $\mu g/m^3$ has been assumed. Eventually the maximum practical stack height is reached and the plant can no longer meet the standards. This defines the infeasible region. No additional abatement method investment can make the plant operate within its air pollution limits.

For both the three hour and twenty-four hour standards, several trends are noticeable. The larger a plant is, the more gradual is the increase in the cost curve as standards are tightened. This is reasonable, if the higher emission rates are considered. These would cause the plant to need extra stack sooner, at standard levels where the next incremental tightening of the standards is a smaller portion of the whole standard level. Thus, smaller stack height additions are needed. For example, in the three hour case, the 1000 MW plant first adds stack height at about 500 $\mu g/m^3$, where the next 100 $\mu g/m^3$ reduction is only a 20% change. The 100 MW plant first adds stack height at 200 $\mu g/m^3$, where the next 100 $\mu g/m^3$ reduction is a 50% change. The 100 MW plant must add stack more quickly as a result.

The larger a plant is, the greater is its infeasible region, as shown best in figure 2.2. This is directly related to two facts. There is the same maximum allowable stack height for all plants and the larger plants have greater stack emissions. Thus the lowest possible concentrations due to a large plant must be greater than those of a smaller plant.

There exist ranges of standards where no capital cost changes result from standards changes. This is due to the fact that the plant pays a base capital price for abatement equipment. This equipment may well put the plant pollution level far below the standard. Additional abatement in the form of added stack is not needed until standards reach the plant pollution level.

The final observation made from model example II is that for this PSA alternative, the twenty-four hour standard is the more critical in terms of economics. All three plant sizes have at least a range of 700 $\mu g/m^3$, or 50% of the present sulfur dioxide three hour air quality standard, before stack height addition is needed. This is reflected in the long flat portions of the three hour curves, extended to 1300 $\mu g/m^3$. In the case of the twenty-four hour standard, it can be seen that the margin is only 25 to 150 $\mu g/m^3$ before stack height is needed, depending on the plant size considered. While this again could be considered in the sense of 50% of the present standard, background levels must be considered.

A 100 $\mu g/m^3$ background level of sulfur dioxide (a reasonable industrial area value) would have no effect on the three hour standard since it would move along the flat part of the curve. A similar increment along the twenty-four hour curve would either require additional stack or put the plant in the position where any additional standards change requires more stack. In using these curves, it should be remembered that they represent a study assuming 50 $\mu g/m^3$ background levels. Thus the 100 $\mu g/m^3$ background just mentioned will only move 50 $\mu g/m^3$ along the curves.

Examples of two of the possible applications of the model were given after providing a model overview and presenting the model operating logic. The next three chapters will explain in detail plant and boiler modeling, meteorological modeling and the inclusion of the abatement methods.

CHAPTER III

BOILER AND STACK EMISSIONS

The first section of the model will be discussed in this chapter, tracing the flow of air pollutants from their origin in the boiler until they are tested against the source emissions standards as they leave the stack. The use of emission factors to predict boiler emissions is explained first, followed by a discussion of the effects of the abatement process on the pollutant stream, and consideration of the emission standards. It is assumed that the reader is familiar with the general operation of the abatement methods. Those wishing an explanation should consult appendix D, which contains a summary of their operating principles and information concerning the chemical reactions involved. The present chapter also discusses the methods used to acquire abatement data and the commercial status of the four methods used in the model.

BOILER EMISSION FACTORS

The uncontrolled boiler output of sulfur dioxide and particulates can be approximated through the use of boiler emission factors. These factors, published by the Environmental Protection Agency,[1] are the results of source tests, material balance studies and engineering estimates. They predict the uncontrolled output of sulfur dioxide and particulates from utility boilers as a function of the amount of fuel being burned and its sulfur and ash contents, given as a weight percentage. The sulfur and ash contents are directly specified as part of the plant specification, and the amount of fuel consumed is easily calculated from two other plant specifications -- boiler heat input and fuel heat equivalent.

Because the boiler emission factors do not differentiate between sulfur dioxide and sulfur trioxide, and because sulfur trioxide formation is just a few percent of sulfur dioxide formation, all oxides of sulfur are considered to be sulfur dioxide. This assumption results in less than two percent error in the calculation of raw material consumption and by-product production in the abatement processes. And since present emission standards apply only to sulfur dioxide, the assumption of all sulfur oxides being sulfur dioxide in no way jeopardizes the plant's adherence to the standards.

When the plant and its fuel are being specified, the choice of sulfur and ash contents are limited to "high", "medium" or "low". Consideration of the properties of different coals and oils suggests the use of the numerical values of table III-1.[33,34] If these values are unacceptable for the problem being studied, they are easily redefined in the model.

For the type of boiler the model deals with, the following emission factors will apply. "S" represents the fuel sulfur content in percent and "A" has the same definition with

TABLE III-1

REPRESENTATIVE SULFUR AND ASH CONTENTS

	Coal S Content	Coal Ash Content	Oil S Content
High	4.5	25.0	3.5
Medium	3.0	15.0	1.5
Low	1.0	5.0	0.5

TABLE III-2

BOILER EMISSION FACTORS

	Cyclone Firing lb/ton of coal	General Firing lb/ton of coal	Oil $lb/10^3$ gal	Gas $lb/10^6$ ft^3
Sulfur Oxides	38S	38S	159S	15
Particulates	2A	16A	8	0.6

respect to ash content. The absence of an "A" or "S" factor indicates that the fuel type has such consistent emission properties that the emission rate of that pollutant is essentially constant. The emission factors are shown in table III-2. The remaining unmentioned plant specification parameters are needed in later model steps, but do not affect the rates of pollutant emission as determined by emission factors.

At this point the model has determined the flow of pollutants leaving the boiler and entering the abatement equipment. There are only two critical factors to be considered in relation to the abatement process' effect on the flow of sulfur dioxide and particulates coming from the boiler. First is the possibility of the abatement process adding to the emissions already coming from the boiler. For example, limestone injected into the boiler during the wet limestone scrubbing process increases particulate flows. Second is the efficiencies of sulfur dioxide and particulate removal accomplished by the process. These determine what quantities of pollutants escape as stack emissions and what quantities are removed to become process wastes or byproducts. The calculation of these additional pollutants and of the process wastes and byproducts is explained in appendix D along with the previously mentioned explanations of process chemistry.

The emissions of sulfur dioxide and particulates, as determined by boiler emissions and abatement removal efficiencies, are then expressed in terms of the plant heat input so as to conform with the emission standards. If either of the standards, for sulfur dioxide or particulates, is exceeded, the plant-site-abatement (PSA) alternative is said to be environmentally infeasible and the remainder of the model is not evaluated.

The abatement methods are one pass devices and little can be done to improve their removal efficiencies from their design values. Because of the low concentrations of sulfur dioxide and particulates in the flue gases, it is not economically attractive to install abatement devices in series. Not only can removal efficiencies suffer when dealing with the extremely dilute gas at the tail end of the first abatement device, but also the cost per pound of pollutant removed can become ten or more times greater since the same volume of flue gas must be treated. Thus, there is no realistic alternative to declaring a PSA combination infeasible if it fails to meet the emission standards with the single abatement device.

If the standards are both met, the emission rates are used in the meteorological modeling portion of the model to check the plant's adherence to the air quality ground level standards.

ABATEMENT PROCESS DATA

As the reader will see in the next chapter on meteorological modeling, models of the atmosphere's dispersion characteristics are empirical and can result in large errors. But they are used because they are the best tools available which enjoy industry wide acceptance. Unfortunately, no such models enjoying industry wide acceptance exist for the abatement methods used in this thesis. This portion of the chapter explains how the particular methods were chosen and how data was obtained for them.

Approximately sixty means of sulfur dioxide removal are currently being or have recently been explored by industry, government and universities. Some of these simultaneously remove particulates, some do not. Perhaps half a dozen methods for particulate removal are commonly used. All together, the possible combinations of sulfur dioxide and particulate removal equipment are far too numerous to be considered in one or even several models.

The problem of choosing a representative set of abatement methods was first approached by searching through the relevant literature. This narrowed the field considerably and the second phase of the search involved writing to about a dozen of the leading developers of sulfur dioxide removal equipment.

The companies were queried on process operations and economics in an effort to determine what factors affected removal efficiencies, power plant operation, capital investment, operating costs and plume behavior. The replies were of varying quality and generally reflected more certainty about process operations than economics. Because of proprietary reasons, ongoing research or lack of operating experience, several manufacturers declined to supply certain operating and cost data.

In the third phase, further literature searching was performed to clarify some of the manufacturers' replies and several utilities with involvement in prototype testing were contacted in hopes of complementing the manufacturers' data. Finally, on the basis of the information gathered from all of these sources, and most importantly, on the basis of an EPA recommendation,[11] the following processes were chosen as representing the best available abatement systems:

a) wet limestone scrubbing
b) catalytic oxidation
c) magnesium oxide scrubbing

"Best" in this case means holding the promise of achieving design aims, having had significant operating experience or contracts to evaluate the process under commercial operation, and being adaptable to relatively straightforward model representation.

It is possible that subsequent prototype testing and operating experience may indicate that these processes are not competitive and some other technology may gain acceptance as the abatement method of the late '70's and '80's. Or it may occur that the same experience may result in drastic process alterations. Either of these eventualities, or some of the arbitrary design decisions made in the specification of the models, may mean that the actual commercial abatement equipment will differ greatly from the models. Due to the embryonic state of the commercial flue gas desulfurization industry and the accompanying absence of accepted operating and costs models, there seems to be no way to protect against the possibility of model obsolescence. Thus the main thrust of the abatement model development has been to maintain flexibility while representing the significant features of each process as they now exist.

COMMERCIAL STATUS OF ABATEMENT PROCESSES

In addition to the above methods of abatement, a fourth was modeled: tall stacks. This method, employing electrostatic precipitators with tall stack heights, is included for contrast and to examine alternatives, such as low sulfur fuel, for which flue gas desulfurization might be unnecessary. Of the four methods, only the tall stack-precipitator combination has had significant operating experience since this is the typical means of controlling air pollution in most existing power plants. The other methods have had prototype experience and limited operating experience but are still subject to possible design changes and new cost estimates. Despite the possibility of such changes, many utilities are now contracting to buy removal installations for future plants in the expectation that by the start up dates, present technical problems will be solved. The three sulfur dioxide abatement methods chosen account for nineteen of the twenty full size installations operating or on order as of mid-1972.

Wet limestone scrubbing (see references 8-20) is offered by several companies, including Combustion Engineering, Babcock & Wilcox, and Research-Cottrell, but Combustion Engineering apparently leads in both operating experience and orders for new systems. Thus its system design was chosen for use in the model as being representative of the general process. To date, plugging, fouling and corrosion due to deposition of calcium sulfate and other solids from the slurry have hampered operations. The problem of safe disposal of the waste products in the settling pond also presents a formidable operating problem for users. This method remains the most popular abatement method being ordered as table III-3 shows.[11] Combustion Engineering's contracts are shown with an asterisk.

Catalytic oxidation (see references 8-12 and 21-23) is exclusively offered by Monsanto Enviro-Chem. This process has been tested for several years on a prototype system for the Metropolitan Edison Company in Pennsylvania, and is being tested with a full size installation by Illinois Power. It has higher capital costs and is more difficult to retrofit onto an existing plant than wet limestone scrubbing. Hence contracts for this process are fewer. Monsanto should be able to demonstrate adequately operating performance with the 100 MW Illinois Power installation. That installation is also being monitored by the EPA to determine system performance and re-

Table III-3

FULL SIZE SO_2 REMOVAL INSTALLATIONS

UTILITY	UNIT	SYSTEM	FUEL
INSTALLED SYSTEMS			
*Kansas Power & Light	Lawrence No. 4 125 Mw	Limestone Scrubbing	3.5% S Coal
*Kansas Power & Light	Lawrence No. 5 430 Mw	Limestone Scrubbing	3.5% S Coal
*Union Electric	Meramec No. 2 140 Mw	Limestone Scrubbing	3.0% S Coal
Boston Edison	Mystic No. 6 150 Mw	Magnesium Oxide Scrubbing	2.5% S Fuel Oil
Commonwealth Edison	Will County No. 1 175 Mw	Limestone Scrubbing	3.5% S Coal
1972 INSTALLATIONS			
*Kansas City Power & Light	Hawthorne No. 3 130 Mw	Limestone Scrubbing	3.5% S Coal
*Kansas City Power & Light	Hawthorne No. 4 140 Mw	Limestone Scrubbing	3.5% S Coal
*Kansas City Power & Light	La Cygne 820 Mw	Limestone Scrubbing	5.2% S Coal
Detroit Edison	River Rouge No. 1 290 Mw	Limestone Scrubbing	3-4% S Coal
Detroit Edison	St. Clair No. 3 180 Mw	Limestone Scrubbing	2.5%-4.5% S Coal
*Louisville Gas & Electric	Paddy's Run No. 6 70 Mw	Limestone Scrubbing	3.0 S Coal
City of Key West	Stock Island 37 Mw	Limestone Scrubbing	2.75% S Fuel Oil
Illinois Power	Wood River 100 Mw	Catalytic Oxidation	3.5% S Coal

Table III-3

(continued)

UTILITY	UNIT	SYSTEM	FUEL
1973-AND-BEYOND INSTALLATION			
Arizona Public Service	Cholla 115 Mw	Limestone Scrubbing	0.4-1% S Coal
Duquesne Light	Phillips 100 Mw	Limestone Scrubbing	2.3% S Coal
Nevada Power Co.	Reid Gardner	Sodium Carbonate Scrubbing	0.5% S Coal
Potomac Electric & Power	Dickerson No. 3 195 Mw	Magnesium Oxide Scrubbing	3.0% S Coal
*Northern States Power	Sherburne County No. 1 and No. 2 1360 Mw	Limestone Scrubbing	0.8% S Coal
*Union Electric	Meramec No. 1 125 Mw	Limestone Scrubbing	3.0% S Coal

sults should be available in late 1973. A major problem appears to be the 77.7% concentration of the byproduct acid, which makes it difficult to find a byproduct market, and adversely affects credits for the process.

The magnesium oxide scrubbing system of the model (see references 8-12 and 24-27) is marketed by Chemico-Basic in a joint effort. Already installed on a Boston Edison plant, this process is being tested by the EPA and the utility. Results should become available also in late 1973. The Essex Chemical Company operates the magnesium oxide recovery plant in Rhode Island. In 1973 Potomac Electric & Power Company will complete installation of the Chemico-Basic system on another plant to gain system operating data and to test further the concept of centralized recovery using crystals from several power plants. Initial problems at the Boston Edison plant involved poor centrifuge performance which resulted in plugging and deposits in the scrubbing liquid system.

All of the three abatement processes which remove sulfur dioxide should begin producing representative operating and cost data by the end of this year, if the new installations solve their initial difficulties. For the present, predicted design data and prototype results give the best feeling for their performance. Performance and costs of precipitators are well established. Stack cost data is highly dependent on the exact site and stack design used, and for this model TVA data was used to determine the parameters of the stack cost equation.[15]

In summary, the model's method of representing the abatement processes will be determined by a need for flexibility to reflect the present scarcity of detailed operating and cost data. No generally accepted models exist at present so the structure of the abatement models primarily will reflect only those aspects important to the general plant air pollution model concept. The actual form of the models is discussed in chapter V.

CHAPTER IV

METEOROLOGICAL MODELING

Once it has been determined that a particular plant-site-abatement (PSA) combination meets the stack emission standards, the ground level concentrations resulting from the emissions must be calculated and compared with the air quality standards for averaging periods of three hours, twenty-four hours and one year. The magnitudes of the ground level concentrations for any given emission rate depend on the effectiveness of the atmosphere in dispersing the stack emissions through transport and diffusion.

This dispersion ability is site dependent and difficult to predict since it results from the turbulent motion of the atmosphere, an inherently stochastic process. Modeling the dispersion of atmospheric pollutants requires considerable familiarity with basic meteorological terminology, and the reader is urged to examine appendix A before proceeding. Many methods of modeling atmospheric dispersion are available and there is no single model applicable to all types of pollution sources. This chapter will explain the models and data used and the qualifying assumptions governing their use.

SITE CHARACTERIZATION

Six different site types can be considered by the model.

These represent three inherently different physical sites, (a coastal location, an inland valley and an inland plain) each capable of being considered with either an urban or rural state of development. Two possible characterizations of the meteorological differences of the sites were considered. First, the possibility of trying to develop models to include explicitly the atmospheric characteristics, such as land and sea breezes or valley channeling of winds, was considered. This would have had the advantages of identifying the individual site dispersion mechanisms explicitly and of representing truly typical generic site types. However the method was rejected for two reasons. This type of modeling is not normal industry practice and would have to be justified, a formidable task! Also, data acquisition and future extension to other site types would be equally formidable.

The characterization chosen lends itself to simple data acquisition, extension to other site types and most importantly, the use of well known and accepted models. This method entails characterizing each physical site type by an array of stability wind rose data which can be used to determine the long term (annual) behavior of the atmosphere at the site. These data are available through the National Climatic Center, or may be obtained at any desired site with relatively simple instruments, although the shorter the observation period, the less representative are the data. Certainly at least one year's data is needed. These data now contain the individual site type dispersion mechanisms implicitly and no longer truly represent a generic site type but rather a single example of the type. As a result they may contain anomalies not found throughout the class of sites. Bearing in mind that the model is not intended to serve as an environmental impact study for all the plants involved, these anomalies are not significant if the data site is carefully chosen to be representative (i.e., don't choose the base of Mt. Washington for a valley data site).

In order to differentiate between urban and rural sites, it was assumed that future "urban" plants, for reasons other than air pollution concerns, will not be built in the urban core, but rather in the adjoining suburban area. This means that they will be removed from the effects of phenomena such as the urban heat island and urban surface roughness, but will still be close enough to be affected by wind borne urban pollutants. Thus future urban plants will not be affected by the uniquely urban meteorological changes as much as they will be affected by the urban contributions to plant background concentrations.

Urban and rural areas were therefore characterized by different background levels of pollutants. These are subtracted from the air quality standards to form the effective standard which the plant must meet. Again, these data are available from the literature[32] or can be determined by testing, although the same problem of observation period length applies.

The valley site requires one additional parameter to account for the aerodynamic effects of the plume's having to rise over the valley walls. The plant is assumed to lie directly within the valley and the sides are considered high enough to cause the ground level maximums to occur as the plume passes over the higher ground outside the valley. Physically, the effective stack height of the plume is reduced by the effect of the valley's walls. The additional parameter for the valley is the altitude above the valley floor of the valley walls. Again, this is only an arbitrary value and does not represent all valleys. Model results must be interpreted in light of the dissimilarities between the physical data and all generic site types.

PLUME RISE

The degree to which the atmosphere can disperse a stream of effluent is directly related to the time and volume of air available for the task. Thus, the higher the initial plume, the longer before its effluent material reaches the ground and the larger the volume of air it mixes with before causing ground level concentrations. Hot power plant plumes can rise considerably before they reach equilibrium with the air and the height they reach above the stack at equilibrium is called the plume rise. Plume rise, Δh, plus the physical stack height, h_s, yields the effective stack height, H.

$$H = h_s + \Delta h \tag{4.1}$$

There are dozens of plume rise formulas available, each derived under different assumptions and applicable to different types of sources. For large power plants (stack heat emission > 20 MW), the most acceptable formula is by Briggs:[4]

$$\Delta h = 1.6\ F^{1/3}\ u^{-1}\ x^{2/3} \qquad x \leq 10\ h_s \qquad (4.2)$$

$$\Delta h = 1.6\ F^{1/3}\ u^{-1}\ (10\ h_s)^{2/3} \qquad x > 10\ h_s \qquad (4.3)$$

where

F = buoyancy flux

u = mean wind speed

x = downwind distance from stack.

These formulas are most accurate in neutral atmospheric stability conditions but apply during unstable conditions as well. During stable conditions Briggs predicts:

$$\Delta h = 2.9 \left[\frac{F}{us}\right]^{1/3} \qquad (4.4)$$

s = buoyant restoring acceleration/unit vertical displacement.

The effective stack height is calculated by (4.1) except in the case of the valley site. There, the streamlines of aerodynamic flow are assumed to be such that:

$$H = h_s + \Delta h - \text{altitude}/2 \qquad H > \text{altitude} \qquad (4.5)$$

$$H = \text{altitude}/2 \qquad H \leq \text{altitude} \qquad (4.6)$$

THREE HOUR WORST CASE AVERAGE

Meteorologically, three hours is a long time period. It is unlikely that any inversion breakup condition or class A stability looping plume, both of which give rise to high ground level concentrations, would persist at one monitoring site for a three hour consecutive period. A more likely case producing high ground level conditions would be the case of neutral to unstable conditions and a limited mixing layer. The worst case would be if the limited mixing layer's elevated inversion were located at the effective stack height. If the inversion occurred any lower the plume would pierce it and not disperse groundward, causing no ground level concentrations at all. If it occurred higher, the plume would have additional mixing volume with smaller ground level concentrations resulting.

The three hour worst case average occurs then with an elevated inversion at the effective stack height and the wind persisting in one direction. The maximum occurs downwind at the distance where mixing first occurs throughout the mixing layer. Concentrations at a closer point would not yet include some of the elevated effluent while at a farther point the increasing sector volume reduces concentrations. The critical distance of complete mixing, $2X_L$, is assumed to be twice the distance at which ground level concentrations first reach 10% of the plume centerline concentrations, X_L. While this choice is arbitrary, it has the advantage of being standard practice in EPA dispersion calculations.[6,7] The actual distance X_L is calculated by solving for X in the equation for σ_z when $\sigma_z = .47L$.

$$X_L = \exp\left[\frac{1}{b}\,\ell n\ ((.47L-c)/a)\right] \tag{4.7}$$

The concentration χ_{3hr} is:[5]

$$\chi_{3hr} = \frac{10^6 Q}{Lu(\frac{2\pi}{16})(2X_L)} \tag{4.8}$$

where

L = mixing height m
Q = emission rate g/s
u = mean wind speed m/s

TWENTY-FOUR HOUR WORST CASE AVERAGE

If three hours was a long period of meteorological time, twenty-four hours, with its diurnal changes added to the problem, makes specification of a worst case even more arbitrary. Again the basic difficulty is the low probability of the wind persisting in one direction for any long period, and simultaneously having poor dispersion. It is first assumed that the same conditions of neutral stability and limited mixing layer apply as in the three hour case. Then we apply the "1/5" law, relating expected maximum concentrations for different observation periods, which states:

$$\frac{\text{maximum concentration}_{\substack{\text{averaging}\\ \text{period one}}}}{\text{maximum concentration}_{\substack{\text{averaging}\\ \text{period two}}}} = \left(\frac{\substack{\text{averaging}\\ \text{period two}}}{\substack{\text{averaging}\\ \text{period one}}}\right)^{1/5} \qquad (4.9)$$

The "1/5" law calculates the maximum expected one hour worst case concentration. It is reasonable and accepted practice then to assume that out of a twenty-four hour period, any receptor will experience only six such one hour maximums.[5] The receptor's twenty-four hour worst case average would then be one quarter of the one hour worst case average in (4.9).

The "1/5" law cannot be directly applied to obtain the twenty-four hour concentration because it is valid only for similar meteorological conditions for both averaging periods. The conditions causing the three hour worst case could never be maintained for twenty-four hours.

By the fact of our derivation of the twenty-four hour worst case from the three hour worst case, both maximums will occur at the same downwind distance $2X_L$. Both the three hour and the twenty-four hour worst case averages depend on the wind speed, through u directly and through L and X_L, both of which depend on u through Brigg's plume rise formula. Generally, as u increases the concentration increases also. Consideration of empirical data from existing plants and the mixing characteristics of the different stability classes led to a choice of B stability with u = 5m/sec as a plausible worst case representation.

ANNUAL AVERAGE

The short term worst case analyses are site independent except for the valley site's reduction of effective stack height. The most significant differentiation of sites on a meteorological basis occurs when the annual averages are concerned. For here the long term characteristics of the atmosphere determine whether the stack effluent is spread thinly over wide areas or continually directed towards one unfortunate location. The critical step is the modeling of dispersion behavior under the different combinations of atmospheric stability and wind speed to yield the ground level concentrations at different distances downwind. Again the model chosen enjoys widespread acceptance, and is straightforward in its use. The general model is the binormal dispersion model of Pasquill and Gifford (see appendix A).[2]

$$\frac{\chi}{Q}(x,y,z,H) = \frac{10^6}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \times \left[\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right] \qquad (4.10)$$

The model is concerned with the maximum of the annual average ground level concentrations. For any combination of wind speed class and stability class, the ground level concentrations will increase, reach a maximum and decrease as distance downwind increases. It is not possible to solve for the distance which maximizes (4.10) analytically, and rather than perform thirty numerical solutions for the thirty wind speed and stability combinations, a set of ten distances, spread over the range of expected maximums (1 to 70 Km) was chosen. It was also assumed that wind frequencies occur evenly in a sector, eliminating the σ_y dependence of (4.10) and producing equal concentrations throughout a sector width at any distance from the stack. Using this assumption, with $y = 0$ giving the plume centerline concentration as representative of the whole sector, and the assumption of ground level concentrations, (4.10) becomes:

$$\frac{\chi}{Q}(x,H) = \frac{2 \times 10^6}{u\sigma_z\sqrt{2\pi}\;\frac{2\pi}{16}\,x} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (4.11)$$

This expression is evaluated for the thirty combinations of wind speed and stability class at each of the ten downwind distances and these values form a 30 × 10 matrix called the concentration factor matrix. This matrix is multiplied by the 16 × 30 matrix of stability wind rose data which has the effect of weighting each concentration by the frequency of occurrence of that wind speed, stability class and wind direction. This forms the 16 × 10 matrix called the ground level multiplier matrix, each element $\overline{\chi}_{i\ell}$ being the annual average concentration per unit of emissions in the i^{th} compass direction and at the ℓ^{th} downwind distance. The matrix multiplication is represented by

$$\overline{\chi}_{i\ell} = \sum_{i} \sum_{j} \sum_{k} F_{ijk} \left(\frac{\chi}{Q}\right)_{jk\ell} \tag{4.12}$$

where

F_{ijk} frequency of occurrence of wind direction i, wind speed class j, stability class k

$\left(\frac{\chi}{Q}\right)_{jk\ell}$ ground level concentration per unit of emissions for wind speed class j, stability class k, distance ℓ.

The elements are then searched for the maximum ground level multiplier. Multiplying its value by the emission rate gives the maximum annual average ground level concentration for each pollutant.

STANDARDS TESTING AND STACK INCREMENTATION

The control variable of the plant is the height of the stack. Ten prespecified values are chosen (100 m to 350 m) with the smallest reflecting the "2½" law, which states that a stack height of at least two and a half times the plant height is necessary to prevent any aerodynamic downwash of the plume. (Actually, any combination of physical stack height and gas exit velocity which achieves the 2½ criteria is acceptable. The model assumes a standard and constant gas exit velocity exists for the plant, so only the stack height determines if the 2½ law is met.)

Using the above formulas, the magnitudes of the three hour, twenty-four hour and annual average ground level concentrations are evaluated. As each of the concentrations is computed, it is compared to the effective site emission standard, i.e. the actual standard minus the existing background for that site. If the computed value exceeds the effective standard, the program returns to the start of the meteorological modeling section, increments the stack height to the next value, and recalculates the various concentrations. This process continues until either a stack height is found for which the three hour, twenty-four hour and annual average standards are satisfied, or until all the prespecified stack heights fail. Failure of all the prespecified stack heights indicates that the PSA alternative under consideration is infeasible and the remainder of the program is deleted.

The use of the stack height as the only controlled design parameter of the plant affecting plume height was deliberate. The alternatives were to control plume rehating or to control plume exit velocity. Plume exit velocity is not normally used as a control method and is assumed constant for this model. Plume reheating entails increasing the buoyant flux of the exit gas stream and is primarily a method of raising the effective stack height.

For large (> 500 MW) plants the incremental cost of plume reheating is most attractive at stack heights above approximately 200 m where additional physical stack height becomes expensive. At lower heights, the relative economic benefits depend on the actual method of reheating (heat exchangers, direct firing of additional fuel, etc.) and overall plant design (gas flows, boiler efficiency, fuel storage, etc.). Plume reheating is not normally used as a design control of plume rise in new plants and would cause complication of both the meteorological and economic portions of the model. Since incrementing the physical stack height produces similar control of the effective stack height, and is considerably more direct in its application, it was used instead of plume reheating or gas exit velocity modification.

Our PSA alternative has been examined now for its compliance with the specified source emission and air quality standards. The final step in the model, discussed in the next chapter, involves determining the economics of the abatement method used.

CHAPTER V

ABATEMENT PARAMETERIZATION AND ECONOMICS

This chapter explains the methods and assumptions used in the model to represent the abatement processes and to calculate the costs of controlling air pollution from a plant-site-abatement (PSA) combination. The reader is referred to appendix D for a complete listing of the model program and parameter names. This chapter explains which costs and parameters are used, why they were chosen and what degree of detail is implied by their use. It should be noted that "costs" is used in a sense which includes both dollars and resources. Thus, fixed capital investment and acres of land needed for flyash disposal are both considered costs. However, no attempt is made to equate resources and dollars other than where a standard conversion exists, for example a cost for supplying 50 gal/sec of makeup process water.

PROCESS PARAMETERIZATION

There are a primary and secondary reason for deciding to parameterize the performance and economics of the abatement process, rather than to determine representative values of parameters and build them directly into the model. The primary reason is to make the model easily adaptable to the system planner's changing data, especially as increased operating experience with the abatement processes results in new values for costs and operating performance. The secondary reason was a desire to make the model flexible enough to be used to examine the sensitivities of pollutant emissions, concentrations and control costs to changes in operating performance or system costs. While such sensitivity studies could be worthwhile in themselves, they are viewed here as just an additional tool to be used to help answer the two basic questions the model addresses: "What is the feasibility of a given PSA alternative?" and "What are the sensitivities of pollution and costs to standards changes?"

The actual number and types of parameters chosen for each process were determined by examining the process operation and by determining what information currently is available in the literature and through manufacturers' reports. Also the degree of detail used in the boiler and meteorological sections would make a great degree of detail in this section a case of "overkill". It was assumed then, that only those aspects of the abatement processes for which data was available (without doing a specific plant engineering study) and which could be found in one of the following groups, would be parameterized:

Group 1: Quantities which affect the emissions or dispersion characteristics of the PSA combination.

Group 2: Quantities affecting the power plant performance.

Group 3: Quantities which determine resource comsumption.

Group 4: Quantities determining raw material use, or wastes and byproduct production.

Group 5: Quantities which describe the maintenance and manpower requirements of the process.

Group 6: Price information needed to represent the dollar costs of process operations.

For discussion purposes, the parameters will be considered in two groups: those which are common to all model abatement methods and those which are peculiar to one or several methods.

COMMON OPERATING PARAMETERS

Parameters common to all abatement method representations, but not necessarily having the same numerical values in all cases, are:

a) SO_2 removal efficiency
b) Particulate removal efficiency
c) Stack gas temperature
d) Stream time
e) Abatement train size
f) Flyash disposal area
g) Operating labor
h) Pump and motor power

SO_2 and particulate removal efficiencies determine both the quantities of emissions and the quantities of byproducts and waste materials produced. Stack gas temperature, the temperature of the gas leaving the abatement process, is needed, along with the boiler exit temperature from chapter II, to calculate F, the buoyancy flux used in the plume rise calculations. These three parameters directly affect the effectiveness of the pollution control equipment and indirectly affect the costs through credits and resource costs.

Stream time is the hours of operation of the plant per year. The annual meteorological dispersion model requires the assumption of 100% operation of the plant during the year to reflect the annual origins of the stability wind rose data. If the plant meets that worst case annual test, it will also meet the standards if the whole plant is off line part of the time. (It will not necessarily meet the standards if the plant is operating but the abatement process is not. This case cannot now be considered by the model.) The stream time of the abatement process must be the same as the operating hours of the plant. Its variability allows a more realistic evaluation of the variable operating costs.

Abatement train size is used to determine, as a function of the gas volume treated, the number of trains needed for the plant. Since several other parameters are given in per train units, this is an important parameter. The train size is considered the maximum gas volume a train can treat, and a whole number of trains must be used. It is assumed that if the calculation of the number of trains exceeds an integer by 0.10, or one tenth of a train, another train will be added. This choice is arbitrary and reflects the fact that only a 10% passage of untreated gas at 90% removal efficiencies can double emissions.

Flyash disposal area is the acres needed for disposal if yearly production is one hundred tons of flyash. The numerical value will depend on whether the ash is collected wet or dry. Since evaporative water losses depend on this parameter, it affects both water and land resource costs. Operating labor is simply the manpower needed to operate the abatement method. Pump and motor power is an aggregate parameter because little data is available to go into more sizing detail. It does not include fan power since fan power depends on flue gas volumes while pumps and motors are determined by the number of trains used. It is used to determine the electrical power needs of the abatement process.

COMMON ECONOMIC PARAMETERS

Parameters common to all abatement method representations are:

a) Train cost
b) Flyash disposal cost
c) System credits
d) Maintenance costs
e) Capital charges
f) Stack height cost coefficients (3)
g) Operating labor cost

h) Supervision cost
i) Plant supplies cost
j) Payroll overhead cost
k) Plant overhead cost
l) Electricity cost

Train cost is the price per kilowatt of capacity for the train size used. The form of this parameter is dictated by the form of the data in most of the literature. Flyash disposal costs is the handling, land and manpower expenses involved in disposing of the flyash. System credits is the market price of the byproduct or any other credits, such as precipitator savings due to scrubber use, that might be under consideration. Maintenance cost for the equipment is expressed as a percentage of the fixed capital investment, this form again coinciding with common literature practice. These four parameters will depend on the process chosen for their numerical values. The values of the remaining eight are usually independent of the process used.

Cost of capital, taxes, insurance, depreciation and interior replacements are all included in capital charges which are expressed as a percentage of fixed capital investment. Stack height cost is represented by a function relating height in meters to costs in thousands of dollars. The functional form is

$$\text{cost} = a(\text{height})^2 + b(\text{height}) + c \qquad (5.1)$$

The stack height cost coefficients are a, b and c. Operating labor cost is simply the wage paid to the operators while supervision cost is a specified percentage of labor. Plant supplies cost is a specified percentage of maintenance costs while payroll overhead is a specified percentage of the sum of labor and supervision costs. Plant overhead is a specified percentage of the sum of labor, supervision, maintenance and plant supplies costs. Finally, electricity cost is the rate paid for the power used in pumps, motors, fans and precipitators.

INDIVIDUAL PROCESS PARAMETERS - WET LIMESTONE SCRUBBING

Additional parameters used to specify the wet limestone scrubbing process are:

a) Limestone $CaCO_3$ content
b) Stoichiometric rate
c) Calcination heat loss
d) Lime products disposal area
e) Pond water loss
f) Scrubber water loss
g) Total pressure drop
h) Limestone cost
i) Lime products disposal costs
j) Makeup water cost
k) Boiler SO_2 conversion

Limestone $CaCO_3$ content specifies the reaction portion of the available limestone. This determines both the limestone required and the additional particulates produced by the limestone injection into the boiler. The stoichiometric rate of $CaCO_3$ injected is related to the SO_2 removal efficiency. In this model the user must correlate the removal percentage and the stoichiometric rate. The model uses the stoichiometric rate to calculate limestone consumption and particulate production. Since some heat energy is needed to calcine the $CaCO_3$ to lime, CaO, the boiler loses efficiency when an injection process is applied. Calcination heat loss determines the change in boiler efficiency. The lime products disposal area is identical in concept to the flyash disposal area mentioned above, only it is for the particulates caused by the limestone and the throw away products of the SO_2 removal reactions.

Wet collection of flyash and process solids produces two kinds of water loss in the system. First, evaporative cooling of the hot flue gases removes water from the scrubber and second, evaporative losses from the disposal pond area removes water from the solids removal system. The amounts of water loss are given by the two water loss parameters, scrubber water loss and pond water loss.

The next parameter, the total pressure drop in the scrubber, gas cooler and reheater, and in the ductwork, is needed to calculate fan power. Fan power, which results in consumption of electrical power, is a function of pressure drop and gas flows.

$$MW_{elec} = 1.955 \times 10^{-1}\, pV \qquad (5.2)$$

p pressure drop, in H_2O

V gas flow ACFM

The limestone cost and makeup water cost are dollar costs for the required raw materials. Water cost appears in all the methods except tall stacks and care should be taken to ensure this value is consistent with that in other methods. The lime products disposal cost is similar to the flyash disposal cost. Since steps must be taken to prevent water pollution by the lime products, this disposal cost will exceed that of flyash disposal. Boiler SO_2 conversion describes the percent of sulfur dioxide emissions converted in the boiler to $CaSO_4$.

INDIVIDUAL PROCESS PARAMETERS - CATALYTIC OXIDATION

Additional parameters used to specify the catalytic oxidation process are:

a) Entrance gas temperature
b) Catalyst loading
c) Catalyst attrition
d) Absorber water consumption
e) Cooling water use
f) Precipitator power requirements
g) Total pressure drops
h) Catalyst cost
i) Makeup water cost
j) Cooling water cost

Entrance gas temperature, the inlet temperature of the gas entering the abatement equipment, is needed to determine gas volumes and train size. Catalyst loading and catalyst attrition together determine the replacement catalyst required after screening. As in the scrubber of the wet limestone process, hot gases in the absorber undergo evaporative cooling and use process water. The rate of consumption is given by the absorber water consumption parameter. The product acid stream cooling water needs are given by cooling water use and the precipitator electric power requirements by the next parameter. The next parameter, describing the total pressure drops within the abatement system, is used to determine the fan power requirements. Since the economiser and preheater would normally be included in the boiler portion of the plant, these drops could be ignored under most circumstances. Or any change in pressure drop caused by making them corrosion resistant could be used as their contribution to the total abatement related pressure drop.

Catalyst cost is the price of the makeup catalyst needed for the system. Makeup water cost is the same parameter used in wet limestone scrubbing and should have the same numerical value. Cooling water cost is a parameter describing the price paid for the water used to cool the acid stream leaving the absorber.

INDIVIDUAL PROCESS PARAMETERS - MAGNESIUM OXIDE SCRUBBING

Additional parameters used to specify the magnesium oxide scrubbing process are:

a) Wetcake water content
b) $MgSO_3 \cdot 3H_2O$ production
c) $MgSO_4 \cdot 7H_2O$ production
d) Initial MgO supply
e) MgO makeup
f) Scrubber water consumption
g) Pond water consumption
h) Acid plant operating share
i) Acid plant investment share
j) Dryer ash emission factor
k) Dryer ash collection efficiency
l) Dryer power requirements
m) Dryer fuel requirements
n) Dryer stack heat
o) Total pressure drop
p) MgO cost
q) Dryer fuel cost
r) Acid plant operating cost
s) Acid plant capital cost
t) Makeup water cost

Depending on the efficiency of the centrifuge, the wetcake entering the dryer will have different percentages of surface water content. Wetcake water content determines this percentage and indirectly affects the water consumption of the process since the surface water is lost in the dryer. The next two parameters specify the effects of the chemical equilibrium in the scrubber by telling what portion of the sulfur dioxide forms crystals of $MgSO_3 \cdot 3H_2O$ rather than $MgSO_3 \cdot 6H_2O$ and what portion forms $MgSO_4 \cdot 7H_2O$. These percentages affect crystal production and water use.

The initial MgO supply and the MgO makeup parameter determine the amounts of magnesium oxide which must be added to the process. Scrubber water consumption and pond water consumption are the same parameters used in wet limestone scrubbing. The pond water results from the wet collection of flyash in the venturi scrubber.

Although the recovery acid plant is not on the power plant site, the power plant may be expected to share in its operating and investment costs. The two acid plant share parameters determine what the percentage participation will be. Of course, an implicit way of reflecting these shares is to lower the price paid for the crystals shipped from the power plant.

The dryer parameters describe its effect on the stack gases of the plant. The ash emission factor predicts the dust the dryer will produce from the wetcake while the collection efficiency refers to the effectiveness of the device between the dryer and the stack used to remove the ash. Both the collection device and the dryer itself will have electric power requirements described by the dryer power requirement parameter. The fuel used in the dryer and the amount of its heat exiting up the stack to assist plume rise are specified by dryer fuel requirements and dryer stack heat.

The following total pressure drop parameter is used to determine the fan power needed, as was done in wet limestone scrubbing. Following it are the parameter for the price of the magnesium oxide makeup required, and the parameter for the price of the dryer fuel. The total operating cost and total capital investment of the acid recovery plant are specified in the next two parameters. Using these and the previous parameters describing the share of the costs the power plant assumes, the actual operating costs and capital the plant must provide are determined. Makeup water cost is the same as in wet limestone scrubbing.

INDIVIDUAL PROCESS PARAMETERS - TALL STACKS

Additional parameters used to specify the tall stacks alternative are:

a) Precipitator power requirements
b) Total pressure drop

The first parameter describes the electric power needed for precipitator operation. The second describes the system pressure drop so that the fan power may be calculated as in wet limestone scrubbing.

PROCESS ECONOMICS

Some feeling for the goals of the economics representation is apparent from reading the choice of parameters for the processes. Specifically, the model calculates three dollar costs and two resource costs, based on one year's operation as defined by the stream time parameter.

a) Total capital investment
b) Total annual fixed operating cost

c) Total annual variable operating cost

d) Water consumption

e) Land usage

In addition, the model also determines the effect the air pollution abatement has on the plant operation through the calculation of the electric power consumption and the change in boiler efficiency caused by the abatement method. No means exists at present in the model to assign a cost to the boiler efficiency change. Electricity costs may or may not be included. At the same time, and under the same control instruction, capital charges, including cost of capital, depreciation, insurance and taxes, may or may not be included in the model's costs. The decision depends on whether the model is used independently or as support for a generation expansion model. Further details on these alternatives are found in appendix B.

The specific equations used to perform the calculations can be found in the program listing of appendix D. The remainder of this chapter is devoted to outlining the calculations. The manner in which the parameters for each process were chosen makes most of the calculations straightforward.

Capital costs consist of two quantities, the installed cost of the inclusive air pollution abatement equipment, and the cost of the stack. "Inclusive" is broadly defined as all the equipment from the exit of the air preheater to the entrance to the stack, including byproduct handling equipment. Stack costs are treated separately since some users might wish to consider the stack as a part of the plant rather than as an air pollution abatement device. Qualifications upon this definition exist for all three sulfur dioxide removal methods.

Wet limestone scrubbing capital costs should also include the costs of the limestone injection equipment and any system modifications necessary to use limestone injection, such as extra slag removal devices in the boiler. Catalytic oxidation capital costs might include the extra capital required for making the air preheater and economizer corrosion resistant. But since these devices are included in a standard plant, their total capital costs should not be assigned to air pollution control, even if they are located physically in the abatement train. Magnesium oxide scrubbing capital costs should include the plant's share in the central chemical processing plant, as specified by the magnesium oxide scrubbing parameters.

Fixed operating costs covers the costs related to air pollution abatement which are independent of the operating hours of the equipment. Capital charges may or may not be included in the fixed operating costs as explained above. Other costs are maintenance costs for the equipment, labor and supervision costs, payroll overhead costs due to the labor and supervision used, and plant supplies and overhead costs. As was explained in the parameterization section, these costs are, with the exception of labor costs, treated as percentages of other predetermined costs. For example, supervision may be considered as 15% of the labor costs. As long as the corresponding percentages for the different abatement methods are the same, reflecting the same accounting procedures, this means of handling fixed operating costs should result in valid comparisons. Of course, maintenance and capital charges will be process dependent.

Annual variable operating costs require more effort and consideration of the actual process operation. These costs (or credits) are generally dependent on some material being consumed or produced. The exception is electric power which depends on pump and motor capacities and the gas flows through the abatement equipment. While electric power consumption is always calculated, it may or may not be included in the variable operating costs, as mentioned earlier. Though material consumption results in costs increasing, production of materials can increase costs, as with flyash which must be dumped, or decrease costs, as with sulfuric acid which can be sold. Theoretically, a high priced byproduct could produce negative variable operating costs, a profit.

Before the actual costs can be calculated, the consumption and production rates of the various process materials must be calculated. These calculations use the process parameters, boiler emission rates, abatement removal efficiencies, and the chemical mass relations of appendix C. Once the consumption and production rates are known, the stream time can be used to determine total annual quantities and the cost parameters can be applied. This results in the total annual variable operating cost. When used as support for the generation expansion model, the variable operating costs are calculated for a stream time of 8760 hours or continuoue operation, and divided by one hundred percent. This results in the so-called "capacity factor adjusted variable operating costs". Multiplication of this number by the plant's actual percentage time of operation in the generation expansion model gives a variable operating cost for the plant. Essentially this is a parameterization of the process' variable operating costs for the generation expansion model. More details can be found in appendix B.

In the process of calculating the required consumption and production rates for the variable operating costs, the water and land consumption of the plant is also calculated. The land consumption is used to determine the physical area of the site and considers the area needed for waste disposal. It is assumed that the equipment space requirements are negligible in comparison. As explained in the parameterization section, the disposal area parameters give the disposal acres required for a yearly output of 100 tons of flyash. If this parameter were .02 acres/100 tons yearly then a yearly production of 200,000 tons would mean the plant must have a disposal area of 40 acres.

All of the important process parameters, the capital costs of the equipment and stack, fixed and variable operating costs and consumption and production rates are output by the cost section of the model program. Credits are normally calculated, but will only be entered into the variable operating costs and output if the user so specifies when he describes the PSA alternative. This allows simple handling of the availability of byproduct markets.

This chapter concludes the explanation of model structure and operation. Conclusions and possiblities for further research are included in chapter VI and appendices with supporting material for the main text follow. In particular, the program listing and data input requirements are included in appendix D.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

A model has been developed for the air pollution control aspects of a fossil fueled steam generating plant. This model has combined several independent modeling techniques to produce an aggregate model capable of two important functions. First, it can evaluate a given combination of a plant, site and abatement method for adherence to specified air pollution standards. Secondly, it can calculate the operating and economic characteristics of the abatement method.

These two functions make the model useful to both system planners and persons responsible for public policy decisions. The model can enable the planner to evaluate and include the effects of air pollution constraints on a generation expansion plan. The policy maker can use the model to examine environmental and economic tradeoffs between different levels of standards. A better understanding of these tradeoffs should enable the policy maker to choose realistic standards which protect both the environment and the consumer paying for electric power.

The two sample uses of the model performed satisfactorily and reflected the expected behavior of a plant's air pollution abatement process. The first sample indicated that of the three and twenty-four hour air quality standards, the twenty-four hour standard was the more critical in determining the feasibility of the sample plant. This was a coal-fired unit of 250 MW, burning 4.5% sulfur coal in a valley site. The second sample tested the capital investment sensitivities to changes in the sulfur dioxide three and twenty-four hour standards. It found that the tradeoff curve is the result of a base equipment cost and a varying stack cost. Of the two present standards, the twenty-four hour is seen as the tighter of the two in terms of abatement capital. Lowering of the twenty-four hour standard is more likely to cause increased capital investment than is lowering of the three hour standard. These results were determined for coal fired plants of 100 MW, 200 MW, and 1000 MW, burning 4.5% coal at a valley site.

FURTHER RESEARCH

The model has been developed and a few simple runs performed. While these produced the expected type of results, further model verification would be helpful. A particularly useful approach would be to test abatement parameter sensitivities with the model. This would determine which parameter values produce results most comparable to manufacturers' data and, in the process, provide the opportunity for continued verification of the model under different PSA alternatives.

Five more specific suggestions are made. First, it would be useful to have some quantitative measure of a site's capability to support a plant's air pollution, in order to rank sites and determine the ultimate limits of site availability. For example, if a site can support a 1000 MW plant, it would be wasted if a 600 MW plant were built. The author believes that using the model with a specified stack height to evaluate sites might be the answer. Say it was desired to rank sites capable of supporting a 500 MW plant with a 250 m stack. Using the model, ground level concentrations could be determined. The margin between these and the standards plus background is a measure of site capacity. A negative margin is an infeasible site and the highest margins could be tested for a 600 MW, 700 MW or 800 MW plant until an infeasible size is found. That last feasible size would be the site capacity.

A second problem is to include the effects of the mixing height in the annual averages. This will be difficult because the mixing height varies with time and would need a probabilistic representation similar to wind rose data. Inclusion of this factor should increase the dispersion capabilities of the plants, making more options feasible.

By simply adjusting the PSA specification and making several program changes, more site types could be represented. The problem here is mainly one of site definition and data acquisition. Site sensitivities could be examined also, especially the question of whether site types or background levels of pollution have the greatest effect on determining feasibility.

The model might be extended in its independent uses to include modeling of the fuel supplies, costs and pollution characteristics. Then it could possibly be determined which fuel is least expensive to use at a PSA alternative if feasibility must be maintained. This would entail replacing the PSA fuel specification with an optimizing fuel choice model.

Finally, it is recommended that the model be applied to the two purposes for which it was designed, generation expansion planning and standards sensitivity studies. Until numerical results are available in these two areas, it is going to be difficult to assess how the model should evolve further. Such application will entail determination of the best parameter values for the plant and its abatement processes, and evaluation of the meteorological results in terms of their effects on plant feasibility. In particular, generation expansion studies with and without air environmental constraints should be done and the economics-air pollution tradeoff curves should be evaluated.

APPENDIX A

METEOROLOGICAL BACKGROUND AND THE BINORMAL DISPERSION FORMULA

This appendix is intended to familiarize the reader with the important meteorological concepts used in Chapter IV on meteorological modeling. More detail is available in references 2 and 3.

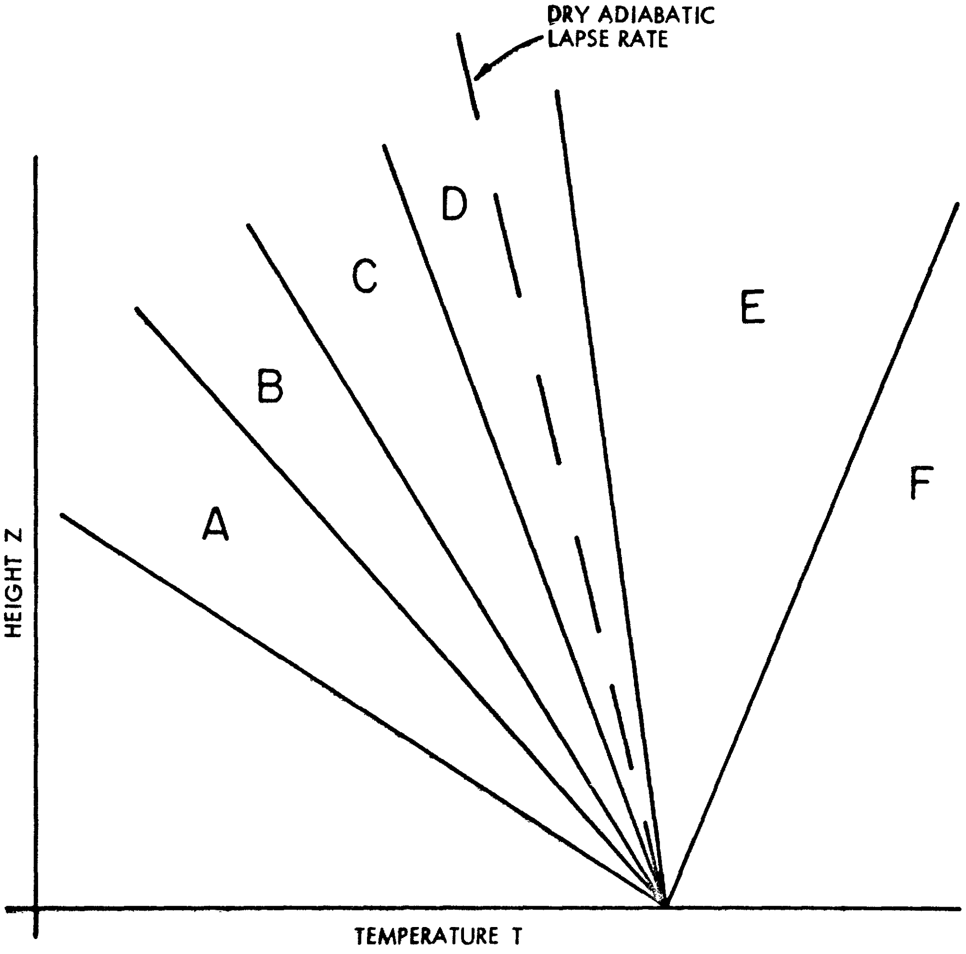
METEOROLOGICAL BACKGROUND

The most obvious influence on atmospheric diffusion is the mean wind speed, which affects both the rate of transport and degree of diffusion of an emitted stream of pollutants. Since increased wind speed provides a greater air volume for diffusion, concentrations are inversely proportional to wind speed. Wind speed and direction are not constant with height since surface objects tend to hinder the passage of air, and ideally the mean wind speed and direction between the plume height and ground level should be used for calculations. Since this is rarely available, surface wind speeds and direction must be used. A listing of the frequency of occurrence of different wind speeds and directions is called wind rose data.

A second, equally important parameter of atmospheric dispersion ability is atmospheric stability. It provides a measure of the thermal turbulence of the air (as opposed to mechanical turbulence caused by the passage of the air over rough surface features). Such turbulence tends to diffuse a plume several orders of magnitude more quickly than simple molecular diffusion and is the chief mechanism for the spreading of plumes through the atmosphere about the mean wind direction. A stable atmosphere is one which damps out the vertical motions of parcels of air. An unstable atmosphere enhances such vertical motions and as a result ensures greater mixing of the atmosphere. Depending on the actual size of the eddies resulting from the vertical motions, such mixing of the air may or may not diffuse the plume. Eddies smaller than the plume tend to diffuse it outwards while eddies larger than the plume transport the entire plume and produce little actual diffusion. The latter condition accompanies a class A stability looping plume and can produce high ground level concentrations as the plume is carried directly to the earth.

An indicator of atmospheric stability is the environmental lapse rate, the vertical distribution of temperature in the atmosphere. The standard of comparison is the dry adiabatic lapse rate (9.8 $^{\circ}$C/1000 m), or the rate of cooling with ascent (or heating with descent) of a parcel of air which experiences no loss or gain of heat from the surrounding air. Under dry adiabatic conditions, when a parcel of air which was originally in equilibrium is forced upwards or downwards, it will still be in equilibrium at its new height. This is considered a neutral stability condition. Superadiabatic, or unstable conditions (lapse rate > dry adiabatic) exist if a parcel is raised (lowered) and at its new height is warmer (cooler) than the air around it, since such conditions would cause the parcel to continue to ascend (descend). Conversely, subadiabatic lapse rates (lapse rate < dry adiabatic), including the isothermal rate, tend to force a displaced parcel back to its original position, causing a stable atmosphere. Extremely stable, or inversion, conditions exist whenever the lapse rate is inverted, i.e. temperature increases with increasing height and little or no vertical mixing can occur. Stability classes range from A, very unstable, to F, strong inversion, with C-D indicating neutral conditions as shown in figure A-1. Table A-1 shows the conditions accompanying each stability class.

If an inversion condition should exist at some height L above the surface, it will form an effective barrier to any further vertical movement and tend to trap pollutants within the layer of air below the elevated inversion. The height of the inversion is the maximum mixing height and the air below it, the mixing layer. The maximum mixing height changes seasonally, monthly and diurnally. Although an elevated inversion best exemplifies a limited mixing layer, a more practical definition of the layer height is the altitude to which a super or dry adiabatic lapse rate is maintained. The effects of various stability conditions on plume behavior are shown in figure A-2.



Lapse Rates and Stability Classes

Figure A.1.

TABLE A-1

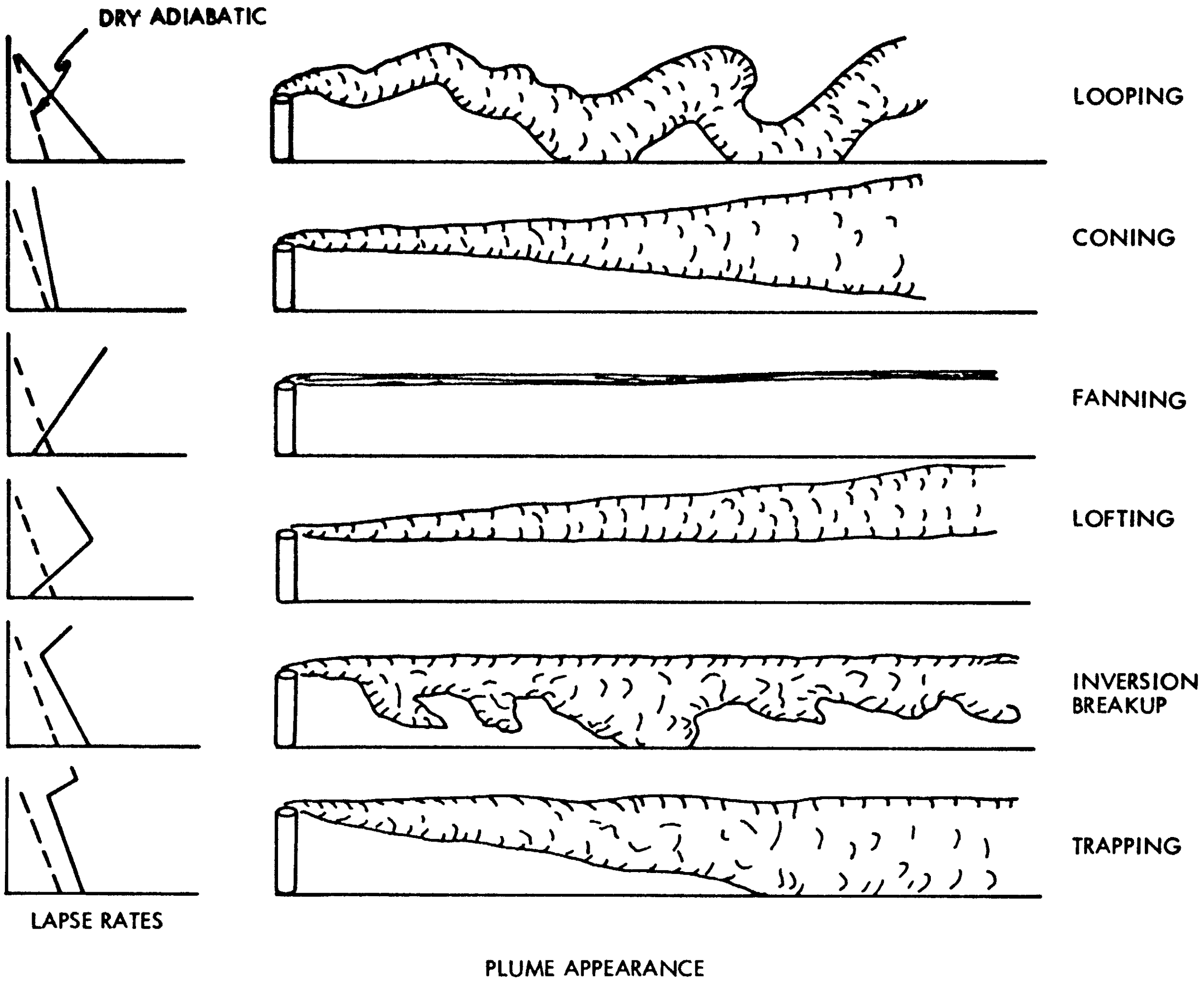
STABILITY CONDITIONS

Surface wind speed, m/sec	Daytime insolation			Nighttime conditions	
	strong	moderate	slight	Thin overcast or 1/8 cloudiness$^+$	3/8 cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
6	C	D	D	D	D

A-extremely unstable conditions
B-moderately unstable conditions
C-slightly unstable conditions
D-neutral conditions*
E-slightly stable conditions
F-moderately stable conditions

* applicable to heavy overcast, day or night

$^+$ the degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.



Plume Behavior

Figure A.2.

When wind data is broken down further, so as to reflect its frequency of occurrence by wind speed and direction, and by the prevailing stability class, the tabulation is referred to as stability wind rose data. For the purposes of this model, and in order to make it compatible with the available National Climatic Center data, stability wind rose data reflects the sixteen compass direction sectors, six wind speed classes (0-3, 4-6, 7-10, 11-16, 17-21 and >21 knots) and only five stability classes (A,B,C,D, and E). These are the five classes originally used by Pasquill and Gifford. Some sets of national climatic center stability wind rose data include class F frequencies and in those cases the frequencies are added to the corresponding class E frequencies.

BINOMIAL DISPERSION FORMULA

$$\frac{\chi}{Q}(x,y,z,H) = \frac{10^6}{2\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \times \left[\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right] \qquad (A.1)$$

$\frac{\chi}{Q}$ = concentration per emission rate $\frac{\mu g}{m^3}/\frac{gm}{sec}$

u = mean wind speed

$\sigma_y \sigma_z$ = standard deviations of the plume concentration in the cross plume and vertical directions (functions

	of X and stability class)
x,y,z	receptor coordinates
H	effective stack height.

This model of the time averaged dispersion of a plume from a source is essentially a statement of continuity based on empirical data from plant observations.[7] It makes the following assumptions:

1) The time averaged plume exhibits a normal distribution of concentrations in the cross plume and vertical dimensions. The standard deviation in the cross plume (σ_y) and vertical directions (σ_z) are considered to be functions of downwind distance and atmosphere stability only.

2) Total surface reflection of the plume occurs at the earth's surface (producing the z+H and z-H terms).

3) The plume description represents conditions averaged over a period of about ten minutes. The mean direction of the plume centerline during this time is the direction of the mean wind.

4) The effluent has neutral buoyancy in the atmosphere and appears to come from a perfect point source located above the stack at the effective stack height.

5) The plume is a steady state phenomenon resulting from a continuous emission source and none of the effluent is removed by chemical or physical action.

6) The coordinate system is shown in figure A-3.

Since this model is being used for ground level concentrations, $z = 0$ and (A.1) becomes

$$\frac{\chi}{Q}(x,y,H) = \frac{10^6}{\pi\sigma_y\sigma_z u}\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (A.2)$$

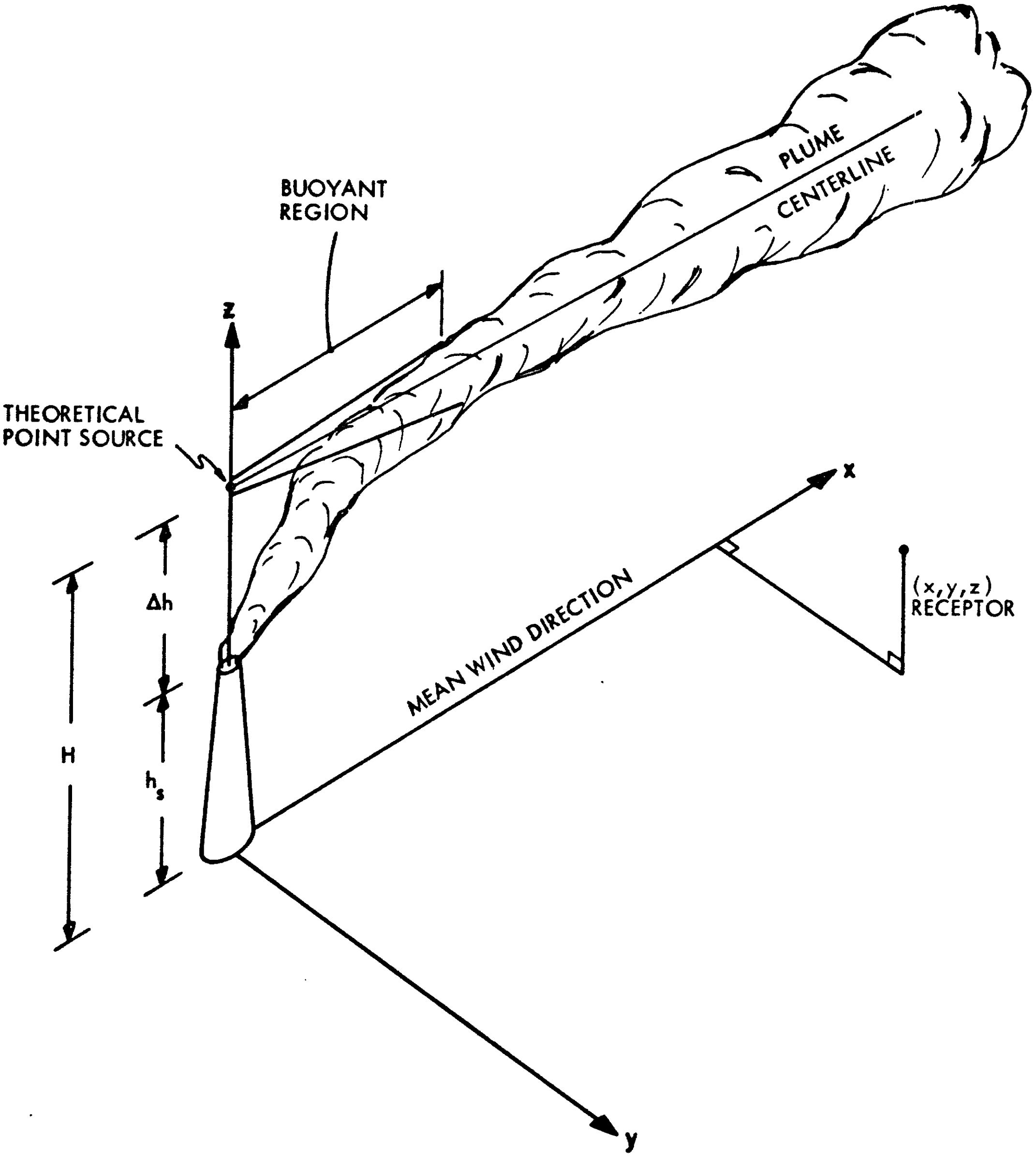
The assumptions were made that over the averaging period the mean wind speed is distributed evenly throughout the direction sector, and that the plume centerline, $y = 0$, represents the concentration across the whole sector width. Sector width equals $2\pi x/16$ and the distribution becomes uninormal, yielding:

$$\frac{\chi}{Q}(x,H) = \frac{2 \times 10^6}{\sqrt{2\pi}\,\frac{2\pi}{16}\,xu\sigma_z}\exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \qquad (A.3)$$

This is the simplified form of (A.1) used in the annual average concentration calculations. Only σ_z remains to be specified.

Pasquill and Gifford developed empirical curves for σ_z of the form

$$\sigma_z = ax^b + c \qquad (A.4)$$



Dispersion Formula Coordinate System

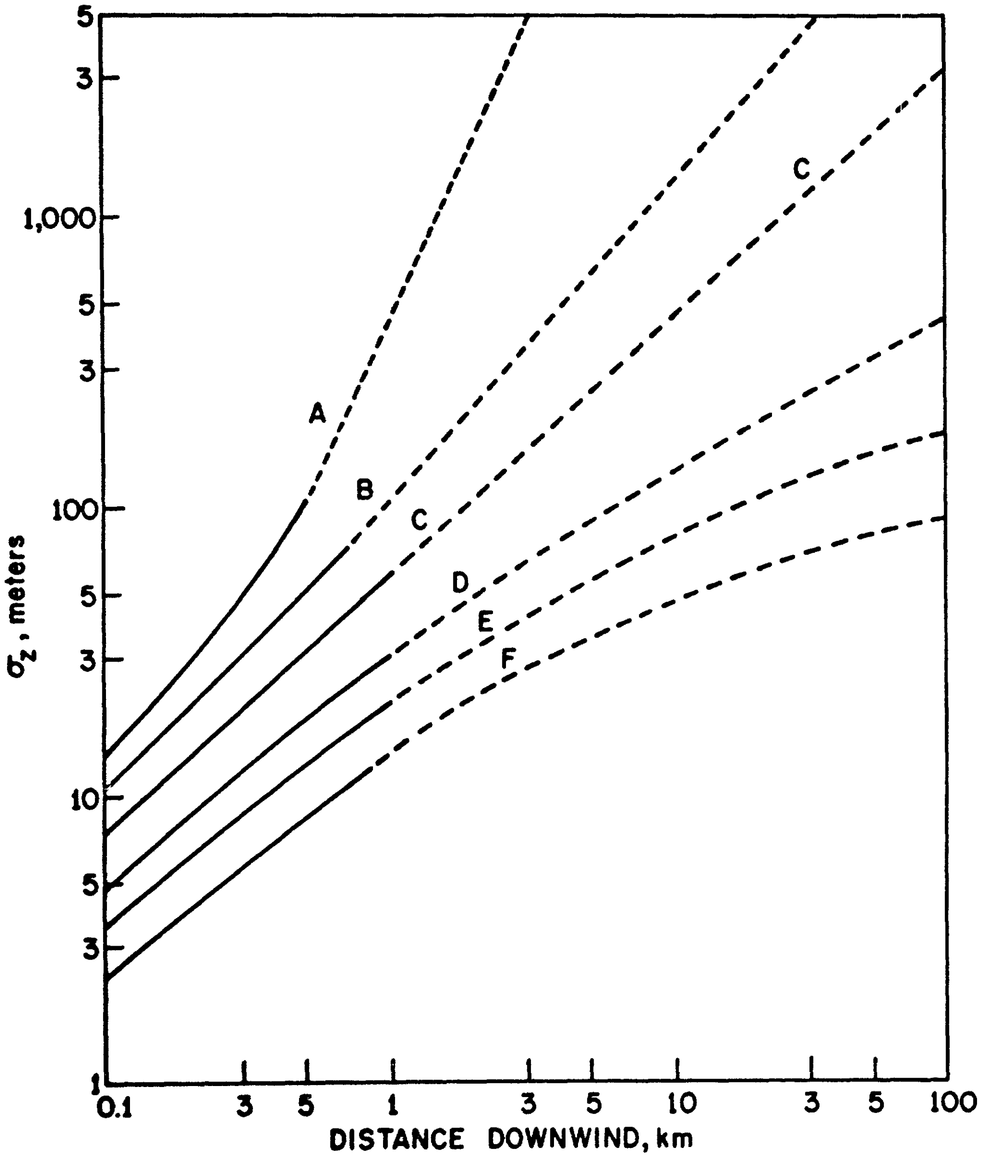
Figure A.3.

with different values of a, b, and c depending on the stability class being considered. The curves are shown in figure A-4 and the table of parameters used is table A-2. Using this empirical data adds additional qualifications to the accuracy of the model, but it remains the best available widely accepted formula for calculating plume dispersion. The outstanding disadvantages are:

1) The empirical data for σ_z was recorded on open flat terrain for travel distances of only a few kilometers. It is therefore questionable for urban areas, areas with surface roughness and for distances over five to ten kilometers.

2) Under the best field conditions, errors of a factor of two are common and a factor of five error is not at all unusual as distance from the source increases.

3) Because of its averaging nature, the formula is not valid for temporary worst case conditions like looping plumes or inversion breakup conditions.



Vertical Dispersion Standard Deviations

Figure A.4.

TABLE A-2

σ_z PARAMETERS

Stability Class		a	b	c
A		0.001	1.890	9.6
B		0.048	1.110	2.0
C		0.119	0.915	0.0
D	$x > 1000$ m	2.610	0.450	-25.5
	$x \leq 1000$ m	0.187	0.755	-1.4
E	$x > 1000$ m	11.61	0.266	-54.7
	$x \leq 1000$ m	0.105	0.771	0.0

APPENDIX B

A GENERATION EXPANSION MODEL

This model could have been developed and used as an independent planning tool. Such a use would dictate a certain straightforward approach to the implementation of the model equations and parameters in a computer program. However, as can be seen from the final model program listing in appendix D, there has not been a straightforward implementation. This is a result of the model's being designed primarily as a subroutine supporting a larger, more complex generation planning program. The air pollution model computer program not only must evaluate the air pollution modeling equations, but also must communicate with the generation expansion planning model.

The reader is urged to examine reference 35 which describes the generation expansion planning model. Such an examination will clarify most of the structure of the air pollution model program. The reader who is concerned only with using the air pollution model independently is referred to appendix D of this thesis which explains data input requirements. It is possible to use the model independently in its present form if the data input requirements are met. The remainder of this appendix briefly explains the use of the air pollution model as a subroutine of the generation expansion model. The issue of modeling gas turbine power plants is also explained.

PLANT EVALUATION MODEL

The generation expansion planning program is actually two models working together. The first, the plant evaluation model, acts as a screening device to select the plant types which are feasible to be used in the second, the plant expansion model. The air pollution model is a subroutine of the plant evaluation model and evaluates the air environmental feasibility of each plant type. An analogous water pollution model exists as a second subroutine to the plant evaluation model.

The operation of the plant evaluation model and the air pollution model subroutine is as follows. The plant evaluation model generates a plant type and site type. It also generates an abatement method and a set of air pollution standards. To these are added data on the site meteorology and background levels, plus data on the plant boiler performance. All of this information, some of it encoded and most not, is passed to the air pollution subroutine "APA" via COMMON storage. A separate data file exists with the abatement parameters. In effect, the plant evaluation model has prespecified a PSA alternative and provided all of the model parameters. As explained in the text, the air pollution model evaluates the air pollution produced and sees if the standards are all met. If they are, the model determines cost and performance data.

Specifically, for each PSA alternative generated by the plant evaluation model, the air pollution model subroutine determines the air environmental feasibility, capital costs, operating costs, resource requirements, power requirement and percent change in boiler efficiency. This information is returned to the plant evaluation model via COMMON and combined with the similar results of the water pollution model. Another PSA alternative is generated and the process continues until all the plant alternatives of interest to the plant evaluation model have been examined.

The plant evaluation model eliminates all those plant combinations which fail to meet the environmental standards. Those that meet the environmental standards have associated with them site and resource requirements, capital and operating costs, fuel consumption data and capacity factor history.

PLANT EXPANSION MODEL

At this point the environmentally feasible plants and their associated data enter the plant expansion model. This linear program chooses the plant types needed to meet demand while minimizing dollar costs, subject to fuel constraints and site availability constraints, among others. Hence this generation expansion program includes environmental constraints through the elimination of environmentally infeasible plant types. This work's air pollution model is designed to perform the elimination function for air environmental standards.

GAS TURBINE MODELING

One major air pollution model addition was needed beyond the changes to facilitate communications with the plant evaluation model. This change was to include a means for evaluating gas turbine generating plants or combined cycle generating plants. (These include a gas turbine generator and a steam generator operating off of the waste heat of the turbine.)

Several major assumptions were necessary to handle the modeling of gas turbines since the air pollution model is designed for steam generating plants with the steam being generated in fossil fueled boilers. These assumptions are:

1) Nitrogen oxide controls are automatically included in all gas turbines considered.
2) Gas turbine emissions of particulates can be predicted by emission factors.
3) The meteorological models used in the model are applicable but stack heights are much lower (<100 m).
4) No air pollution abatement devices are applied.

The first assumption was made because nitrogen oxide control through water or steam injection is presently feasible and the EPA is now considering standards which would essentially require such control. Also this assumption is consistent with the general model's assumption of considering only particulates and sulfur dioxide.

The second assumption is made for modeling convenience since such emission factors do not exist at present. The values used are the results of discussions with EPA staff and turbine engineers. It can be expected that with increased use of gas turbines by the power industry, EPA will determine gas turbine emission factors. The values used are:

TABLE B-I

GAS TURBINE EMISSION FACTORS

	Dist. Oil/10^3 gal	Nat. Gas/10^6 ft^3
SO_2	142S	.6
Particulate	15	7.5

The distillate values are taken from the EPA EF booklet for stationary sources.[1] The natural gas values are taken from the same booklet, with an arbitrary half the particulate value used. This is an attempt to reflect the cleaner operation of a gas turbine compared with a boiler system. It is expected that gas turbines will always be feasible for sulfur dioxide and particulates if these clean fuels are used. The choice of EF should ensure that the model operates in the expected way. The real feasibility restrictions on gas turbines are due to nitrogen oxides, which the model presently does not consider.

The high heat ejection of gas turbines would tend to make buoyancy effects dominate during plume rise. Briggs' formulas should still be applicable. The gaussian diffusion equation simply is a conservation of mass relationship and should apply. The smaller size of gas turbine units indicate that smaller stacks would be used. An exception would be in the case of proximity to an operational stack which could accept the turbine output. Without such proximity, stack heights will probably range from 20 m to 70 m. These are arbitrary values reflecting current practice. Corresponding to the reduced dispersion of a lower stack, the downwind distances examined are reduced by a factor of ten, ranging from 100 m to 7 Km.

Since low-polluting fuels are normally used in gas turbines, it would very rarely be reasonable to construct any stack gas treatment facilities. The cost of gas turbine stack will be negligible also, so abatement costs are zero.

These assumptions and the accompanying additions to the basic model are made to allow the "APA" subroutine to evaluate gas turbine plants. It can be expected that gas turbine emission standards will differ from fossil steam generating plants as well. The logic of determining the correct standard is the responsibility of the plant evaluation model.

APPENDIX C

ABATEMENT PROCESSES DESCRIPTIONS

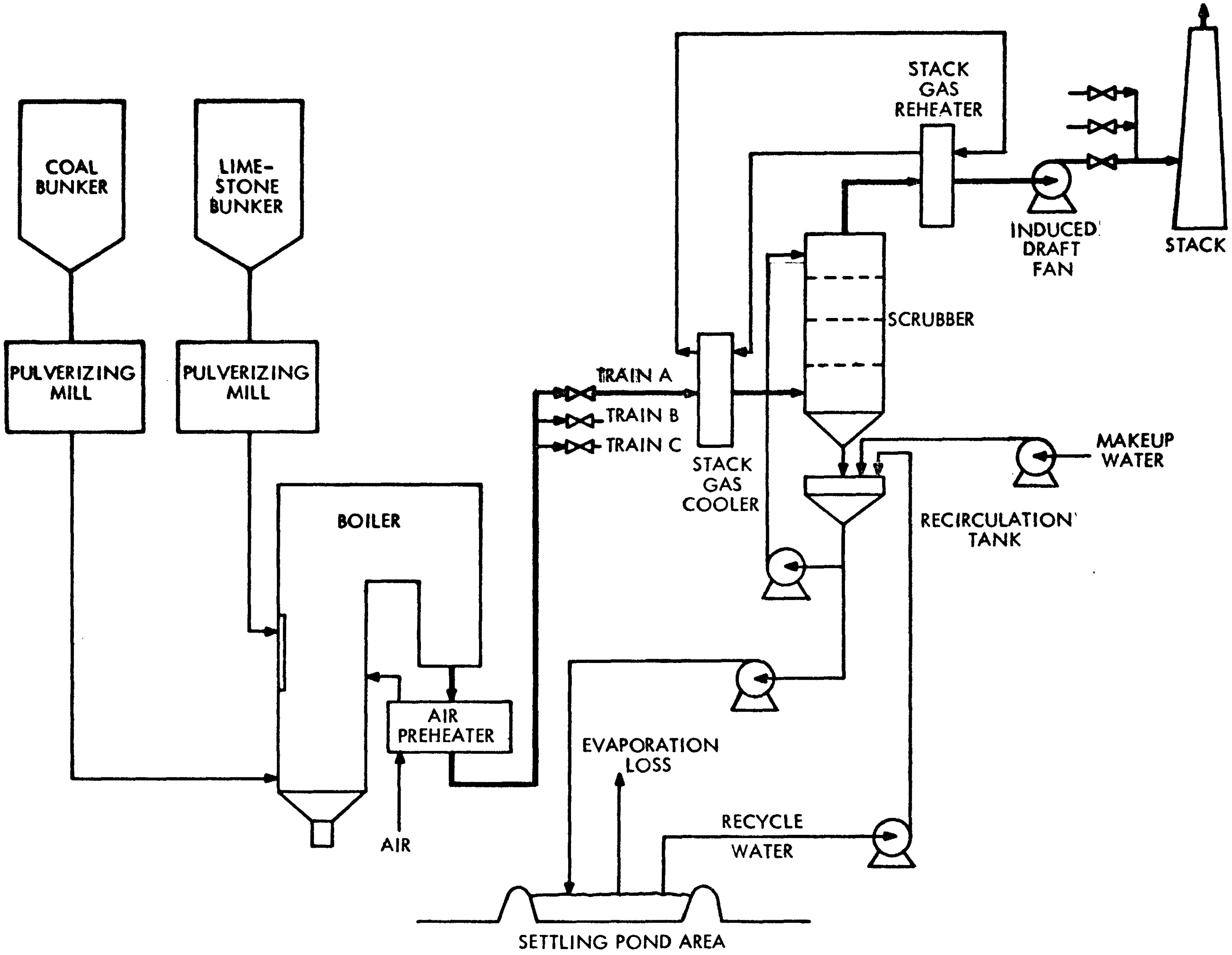
This appendix describes the operation of the four abatement processes used in the model. The information was gathered from the available literature and manufacturers' reports, and from personal correspondence with representatives of the manufacturers. The main references used are listed in the reference section. While most of these sources suggest several possible equipment configurations which could be applied to a plant under different circumstances, it was necessary to decide on one particular configuration for each process to be modeled. This decision has to be somewhat arbitrary without a specific plant in mind, but an effort was made to ensure that the various models would yield valid comparisons. A comparitive study of sulfur dioxide control processes was used frequently to try to attain this valid comparison basis.[3] Each process is described in three steps. First the overall process and equipment is explained. Second, the important chemical reactions are examined. And finally, making use of some of the model parameters explained in chapter V, the equations determining material consumption and waste and byproduct formation are reviewed. These are basically conservation of mass equations.

WET LIMESTONE SCRUBBING

The wet limestone scrubbing process removes sulfur dioxide at two locations, in the boiler and in a scrubber. Particulate matter is collected wet in the scrubber and no precipitators are needed. It is a throw away process and can achieve removal efficiencies of 85% to 90% for sulfur dioxide and 98% or better for particulates.

As shown in figure C.1, a pulverized additive such as limestone ($CaCO_3$) is added directly into the furnace with the fuel. The heat of the furnace calcines the carbonate to a base (CaO) and some sulfur dioxide reacts in the boiler with the base to form sulfates. This can cause a loss in boiler efficiency if extra fuel is not supplied to provide the heat of calcination. The resulting boiler exit flue gas will contain not only particulates from the fuel, but also particulates from the limestone impurities, $CaSO_4$ from the reaction of sulfur dioxide and CaO, and CaO, which is not inert like the other particulates.

Due to the limitations of scrubber capacity, the boiler exit gas stream may be broken into several identical parallel scrubber trains. A single train begins with a heat exchanger system which will eventually reheat the cooler scrubber exit gases. From the heat exchanger, the sulfur dioxide and particulate laden gases are passed through a counter current circulating scrubbing solution. This solution, formed by the



Wet Limestone Scrubbing
Figure C.1.

reaction of water with the calcination products, completes the sulfur dioxide-CaO reactions. The inert solids, captured by impaction and entrainment into the scrubbing solution stream, are also removed. A mist eliminator follows the scrubber. The exiting flue gases, cooled by evaporative water loss from the scrubbing solution, are reheated by the heat exchanger and enter the stack through induced draft fans.

The liquid effluent of the scrubber is removed to a holding tank for several minutes to allow controlled crystallisation of the $CaSO_4$ product so as to prevent system plugging. A purge stream carries $CaSO_4$, flyash and $Ca(OH)_2$, produced by the hydration of unreacted CaO, from the scrubber liquid cycle to a settling pond. Makeup water must be added to the system to replace evaporation from the settling pond and from the scrubber solution. The products in the settling pond must be handled and stored with care because they have a high water pollution potential.

The process chemical reactions are as follows:

$$CaCO_3 \xrightarrow{\Delta} CaO + CO_2 \tag{C.1}$$

Boiler reactions

$$CaO + \tfrac{1}{2}O_2 \longrightarrow CaSO_4 \tag{C.2}$$

$$2CaO + H_2O + 2SO_2 \xrightarrow{O_2} CaSO_4 + CaSO_3 + H_2O \tag{C.3}$$

Scrubber reactions

$$CaO + SO_3 \longrightarrow CaSO_4 \tag{C.4}$$

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad \text{Hydration reaction} \tag{C.5}$$

As justified in chapter III, all sulfur oxides are considered to be sulfur dioxide, so equation (C.4) is not used to describe scrubber reactions in the model.

The equations marked by asterisks, determining limestone consumption, waste solids production, additional particulate loading and chemical water consumption are based on the conservation of mass principle, and require several wet limestone scrubbing process parameters.

CaO	- 56 g/mole	$CaSO_4$	- 136 g/mole
$CaCO_3$	- 100 g/mole	H_2O	- 18 g/mole
SO_2	- 64 g/mole	$Ca(OH)_2$	- 74 g/mole

$CaSO_3$ - 120 g/mole

$$CaCO_3 \text{ used} = \frac{100}{64} \times (SO_2 \text{ emissions}) \times \left(\frac{\text{Stoichiometric \%}}{100}\right) \tag{C.6}$$

$$* \text{ Limestone used} = \frac{(CaCO_3 \text{ used}) \times 100}{\% \; CaCO_3 \text{ in limestone}} \tag{C.7}$$

$$* \text{ Excess particulates} = (\text{non-reactive limestone}) + (\text{boiler } CaSO_4) \tag{C.8}$$

$$\text{non-reactive limestone} = \frac{100 - (\% \; CaCO_3 \text{ in limestone})}{100} \times (\text{limestone used}) \tag{C.9}$$

$$\text{boiler } CaSO_4 = \frac{136}{64} \times (SO_2 \text{ emissions}) \times \frac{(\%\ SO_2 \text{ boiler conversion})}{100} \tag{C.10}$$

$$* \text{ Wastes production} = (\text{scrubber waste solids}) + (Ca(OH)_2 \text{ wastes}) \tag{C.11}$$

$$\begin{aligned}\text{Scrubber waste solids} = {} & \left(\frac{\%\ \text{particulate removal}}{100}\right) \\ & \times (\text{particulate emissions} + \text{excess particulates}) \\ & + \frac{128}{64} \times (SO_2 \text{ emissions}) \\ & \times \frac{(\%\ SO_2 \text{ removal} - \%\ SO_2 \text{ boiler conversion})}{100}\end{aligned} \tag{C.12}$$

$$Ca(OH)_2 \text{ wastes} = \frac{74}{56} \times (CaO \text{ from boiler}) \times \frac{(100 - \%\ SO_2 \text{ removal})}{100} \tag{C.13}$$

$$CaO \text{ from boiler} = \frac{56}{100} \times (CaCO_3 \text{ used}) \times \frac{(100 - \%\ SO_2 \text{ boiler conversion})}{100} \tag{C.14}$$

$$* \text{ Water consumption} = \frac{18}{74} \times (Ca(OH)_2 \text{ wastes}) \tag{C.15}$$

Excess CaO is not inert in the scrubber so it is not considered part of the excess particulate loading. The excess particulates are subject to being deposited in the boiler as are normal particulates. As a result, equation (C.8) has an emission factor included when it is used in the model. The change in boiler efficiency caused by the calcination heat requirements is given by:

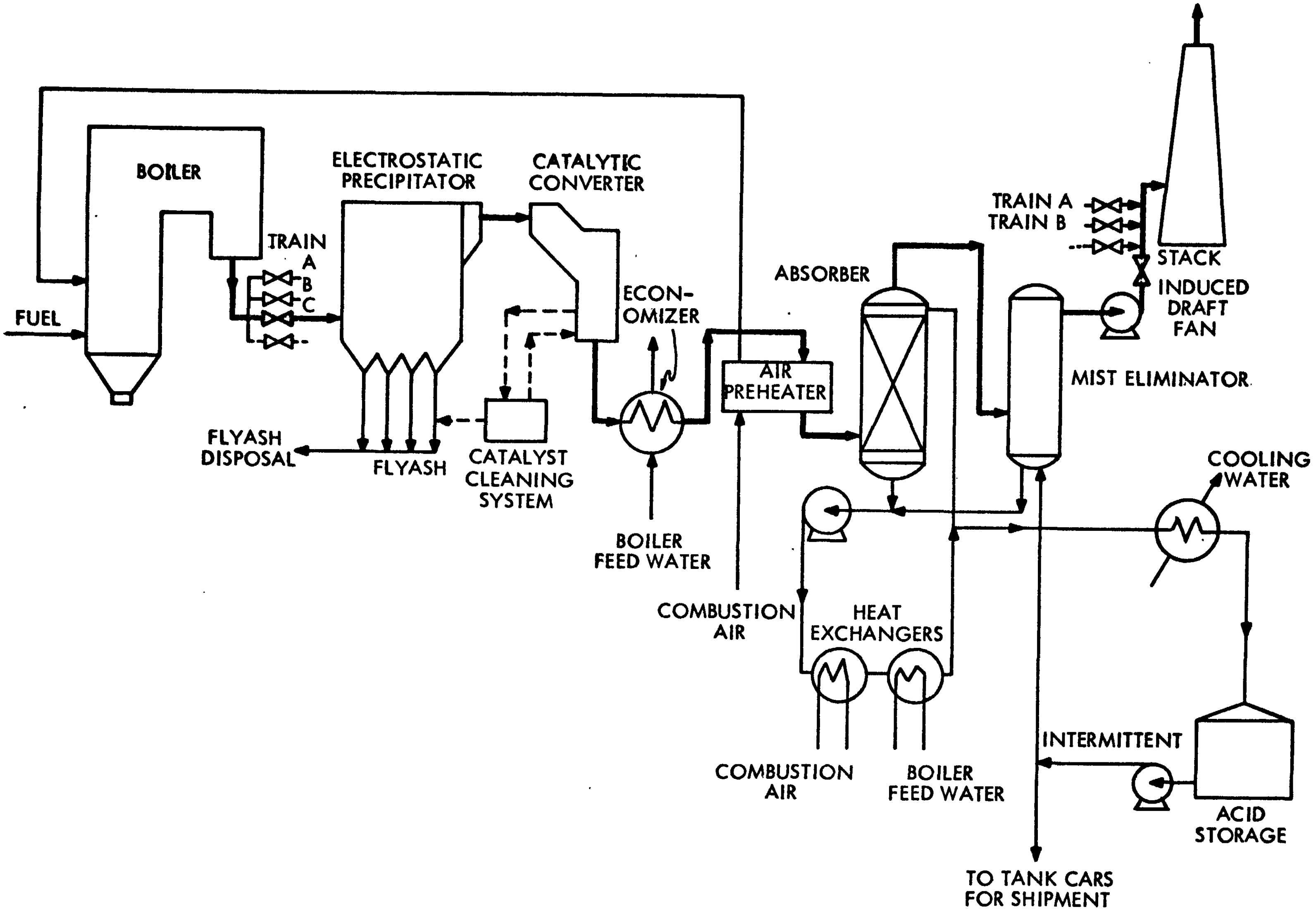
$$\text{Boiler efficiency change} = \left(\frac{\text{calcination heat}}{\text{ton } CaCO_3}\right) \times \frac{(\text{tons of } CaCO_3)}{(\text{boiler heat input})} \times 100 \qquad (C.16)$$

Alternatives to this configuration are numerous. Dolomite ($CaCO_3:MgCO_3$) can be substituted for limestone. Precipitators can be used. No boiler injection at all is possible if lime is added directly to the scrubber solution. However, the configuration described in detail above is believed to be the most attractive commercially available limestone scrubbing system at present.

CATALYTIC OXIDATION

Catalytic oxidation is a byproduct process relying on the high temperature action of a vanadium pentoxide catalyst to convert sulfur dioxide to sulfur trioxide. The sulfur trioxide is then converted to low grade (77.7%) sulfuric acid.

As shown in figure C.2 the installation of a Cat-Ox system on a new power plant requires relocation of the economizer



Catalytic Oxidation

Figure C.2.

and air preheater in order to provide the flue gas at the correct operating temperature for the catalyst, between 850 ^{o}F and 900 ^{o}F. The extra ductwork and plant design changes needed are considered more economical than adding reheaters after the precipitators, as would be done on a commercial back fitted unit. The high gas temperature also requires that a greater gas volume be treated and that high temperature electrostatic precipitators be used. High efficiency dust collection is vital since dust and particulate matter tend to clog and plug the catalyst beds, necessitating more frequent cleaning and correspondingly greater catalyst attrition. Normally the catalyst beds of the converter must be cleaned four times a year, and experience about 2% attrition with each cleaning.

The high temperatures guarantee efficient oxidation of the sulfur dioxide to sulfur trioxide by the catalyst's action in the catalytic converter. About 90% of the sulfur dioxide is converted and 99% removal of particulates is possible in the precipitators. The flue gas proceeds through the economizer and air preheater, both of which must be designed to withstand the corrosive ability of the sulfur trioxide, and enters the packed bed absorbing tower. Here it is cooled by a stream of dilute sulfuric acid and the sulfur trioxide present reacts with the excess water to form additional 77.7% sulfuric acid.

The sulfuric acid is cooled as it leaves the absorbing tower and part of the acid flow is cycled back to cool later gas while part is bled off to storage for later sale. A demister is added to remove any corrosive acid droplets the stream may have acquired, and the gas, now at about 250 °F after evaporative cooling in the absorbing tower, exits directly to the stack through induced draft fans. No reheating equipment is needed. As in the case of wet limestone scrubbing, limitations in the capacity of the converter or absorbing tower may make several identical parallel trains of equipment necessary.

The chemical reactions of the process are:

$$2SO_2 + O_2 \xrightarrow{\substack{\text{CATOX A}\\ \text{CATALYST}}} 2SO_3 \quad \text{Catalytic Converter} \qquad (C.17)$$

$$SO_3 + H_2O \longleftrightarrow H_2SO_4 \quad \text{Absorbing tower} \qquad (C.18)$$

The asterisked equations determining water consumption and acid production are based on the conservation of mass principle and require several catalytic oxidation process parameters.

SO_2 - 64 g/mole H_2O - 18 g/mole H_2SO_4 - 98 g/mole

$$100\%\ H_2SO_4 \text{ produced} = \frac{98}{64} \times (SO_2 \text{ emissions}) \times \frac{(\%\ SO_2 \text{ removal})}{100} \qquad (C.19)$$

$$H_2O \text{ in } 100\%\ H_2SO_4 = \frac{18}{98} \times (100\%\ H_2SO_4 \text{ produced}) \qquad (C.20)$$

$$* \text{ Total } 77.7\% \ H_2SO_4 = \frac{100\% \ H_2SO_4 \text{ produced}}{0.777} \tag{C.21}$$

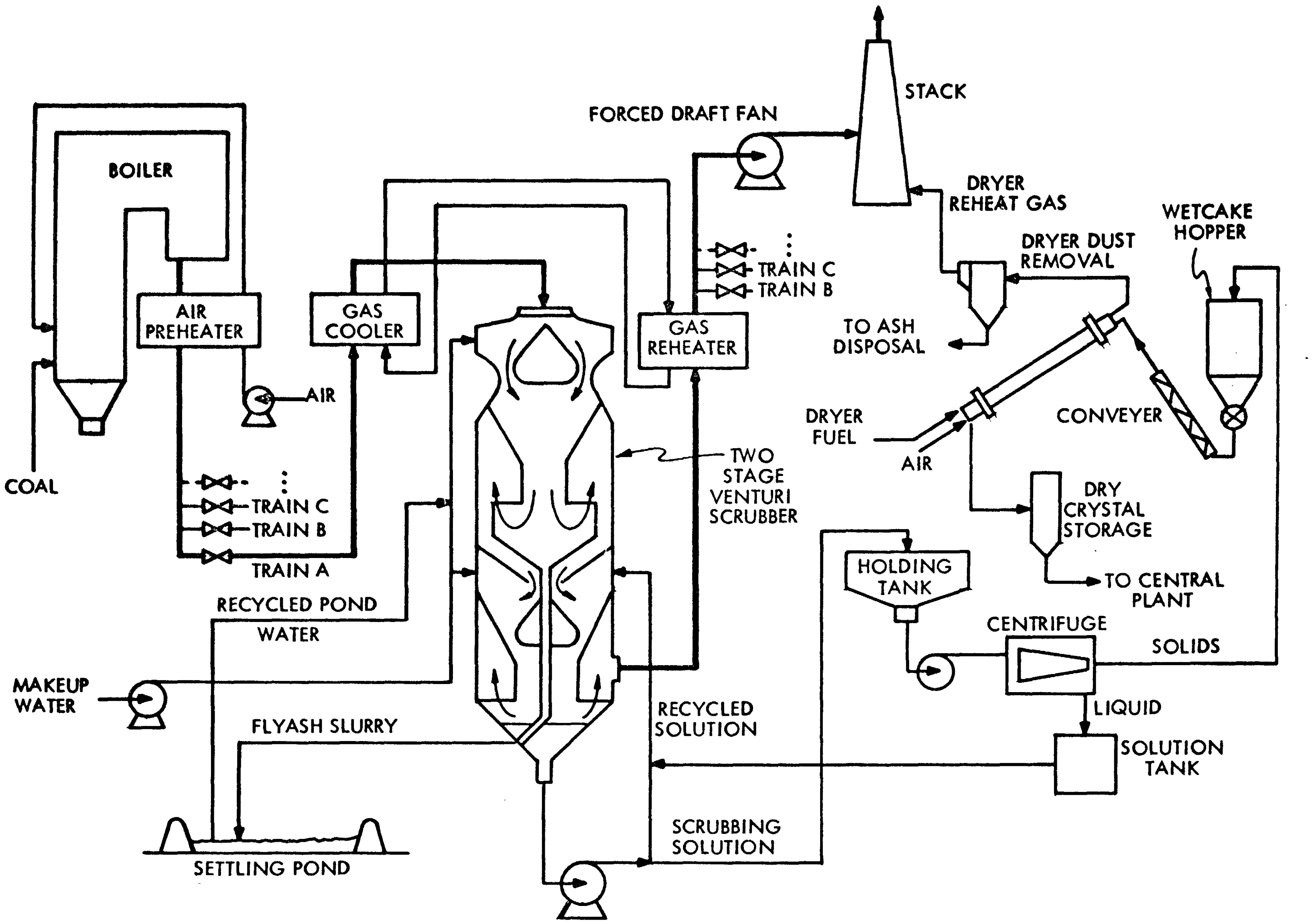
$$* \text{ Total } H_2O \text{ used} = (H_2O \text{ in } 100\% \ H_2SO_4) + 0.223 \times (\text{total } 77.7\% \ H_2SO_4) \tag{C.22}$$

There should be no effect on boiler efficiency by the use of this process. The major alternative to this configuration was already mentioned: using standard plant design of the economizer and air preheater and reheating the gas as it leaves the precipitators. Except where physical conditions, such as retrofitting a plant, require such an installation, it is believed that the detailed system is the more promising.

MAGNESIUM OXIDE SCRUBBING

Magnesium oxide scrubbing is a byproduct process using a closed cycle recovery method and the concept of centralized recovery to produce concentrated sulfur dioxide, sulfuric acid or elemental sulfur.

As is shown in figure C.3 a two stage venturi wet scrubber is used to collect flyash and to react the flue gas sulfur dioxide with a slurry of water, magnesium oxide, magnesium sulfite and magnesium sulfate. The first stage of the venturi scrubber collects the flyash by impingement upon the water droplets injected into the scrubber. The resulting stream of water and ash is diverted to a settling pond for disposal.



Magnesium Oxide Scrubbing
Figure C.3.

Entering the second scrubber stage, the sulfur dioxide present in the gas diffuses into the slurry droplets and forms hydrated sulfites of magnesium. Side reactions form some sulfates. The flue gas and the entrained scrubbing slurry pass to the base reservoir of the scrubber where the slurry is collected. The gas passes through baffle type mist eliminators and exits into the stack. Some particulate matter escaping the first stage is removed in the second yielding an overall particulate removal efficiency of over 98%. Sulfur dioxide removal is about 90% effective.

The slurry is bled from the reservoir of the scrubber to a centrifuge which separates the hydrated crystals formed from the sulfur dioxide reactions and, in the process, removes some of the magnesium oxide crystals also. The centrifuge solution is recycled to the scrubber and the centrifuge wetcake is sent to a dryer to remove both the surface water and water of crystallization. The dryer operates on its own fuel supply and releases its flue gases into the stack where they provide reheating for the scrubber gas. Before entering the stack the dryer flue gases pass through a dust removal device (precipitator, cyclone, etc.) to remove the particulates caused by the wetcake drying process.

After a sufficient quantity of dried crystals is amassed on the plant site, they are shipped to the central processing plant. There the crystals are calcined, releasing a stream of concentrated sulfur dioxide and regenerating the magnesium oxide. The sulfur dioxide stream can be sold, converted into 98% sulfuric acid or made into elemental sulfur, depending on the market demand and the central processing plant's facilities. The regenerated magnesium oxide, plus some makeup, is returned to the power plant to form the scrubbing slurry.

The reactions used in the process are as follows:

$$MgO + SO_2 + 6H_2O \longrightarrow MgSO_3 \cdot 6H_2O \tag{C.23}$$

Scrubber
Reactions

$$MgO + SO_2 + 3H_2O \longrightarrow MgSO_3 \cdot 3H_2O \tag{C.24}$$

Side reactions are:

$$MgO + SO_3 + 7H_2O \longrightarrow MgSO_4 \cdot 7H_2O \tag{C.25}$$

$$MgSO_3 + \tfrac{1}{2}O_2 + 7H_2O \longrightarrow MgSO_4 \cdot 7H_2O \tag{C.26}$$

$$MgSO_3 \cdot 6H_2O \xrightarrow{\Delta} MgSO_3 + 6H_2O \tag{C.27}$$

$$MgSO_3 \cdot 3H_2O \xrightarrow{\Delta} MgSO_3 + 3H_2O \tag{C.28}$$

Dryer
Reactions

$$MgSO_4 \cdot 7H_2O \xrightarrow{\Delta} MgSO_4 + 7H_2O \tag{C.29}$$

$$MgSO_3 \xrightarrow{\Delta} MgO + SO_2 \tag{C.30}$$

Calciner
Reactions
(Cental Plant)

$$MgSO_4 + \tfrac{1}{2}C \xrightarrow{\Delta} MgO + SO_2 + \tfrac{1}{2}CO_2 \tag{C.31}$$

As justified in chapter III, all sulfur oxides are considered to be sulfur dioxide, so equation (C.25) is not used to describe scrubber reactions in the model.

The asterisked equations determining chemical water consumption and production of crystals are based on the conservation of mass principle and require several magnesium oxide scrubbing process parameters.

MgO - 40 g/mole
SO_2 - 64 g/mole
H_2O - 18 g/mole
$MgSO_4$ - 120 g/mole
$MgSO_3$ - 104 g/mole
$MgSO_3 \cdot 3H_2O$ - 158 g/mole
$MgSO_3 \cdot 6H_2O$ 212 g/mole
$MgSO_4 \cdot 7H_2O$ - 246 g/mole

$$* \text{ Water consumption} = (\text{surface water loss}) + (\text{3 hydrate loss}) + (\text{6 hydrate loss}) + (\text{7 hydrate loss}) \qquad (C.32)$$

$$\text{3 hydrate loss} = 3 \times \frac{18}{64} \times (SO_2 \text{ emissions}) \times \frac{(\%\ SO_2 \text{ removal})}{100} \times \frac{(\% \cdot 3H_2O \text{ formation})}{100} \qquad (C.33)$$

$$\text{7 hydrate loss} = 7 \times \frac{18}{64} \times (SO_2 \text{ emissions}) \times \frac{(\%\ SO_2 \text{ removal})}{100} \times \frac{(\%\ MgSO_4 \text{ formation})}{100} \qquad (C.34)$$

$$\text{6 hydrate loss} = 6 \times \frac{18}{64} \times (SO_2 \text{ emissions}) \times \frac{(\%\ SO_2 \text{ removal})}{100} \times \frac{(100 - \% \cdot 3H_2O \text{ formation} - \%\ MgSO_4 \text{ formation})}{100} \qquad (C.35)$$

$$\text{surface water loss} = (\text{crystals weight}) \times (\%\ \text{surface water}) \qquad (C.36)$$

$$\text{crystal weight} = (SO_2 \text{ emissions}) \times \frac{(\%\ SO_2 \text{ removal})}{100}$$

$$\times \frac{100}{100 - \%\ \text{surface water}}$$

$$\times \frac{158 \times (\%\cdot 3H_2O \text{ formation}) + 246 \times (\%\ MgSO_4 \text{ formation})}{64 \times 100}$$

$$+ \frac{212 \times (100 - \%\cdot 3H_2O \text{ formation} - \%\ MgSO_4 \text{ formation})}{64 \times 100} \qquad (C.37)$$

A major modeling assumption was made that the central processing plant need only be represented as a service to the power plant for which the power plant must assume certain shares of both the central plant's operating costs and capital investment. Also, it was assumed that the power plant produces crystals as its byproduct rather than the ultimate acid or sulfur dioxide that results. Perhaps the major change possible in the process is the substitution of a single stage scrubber and precipitator for the two stage venturi scrubber, which is more expensive.

TALL STACKS

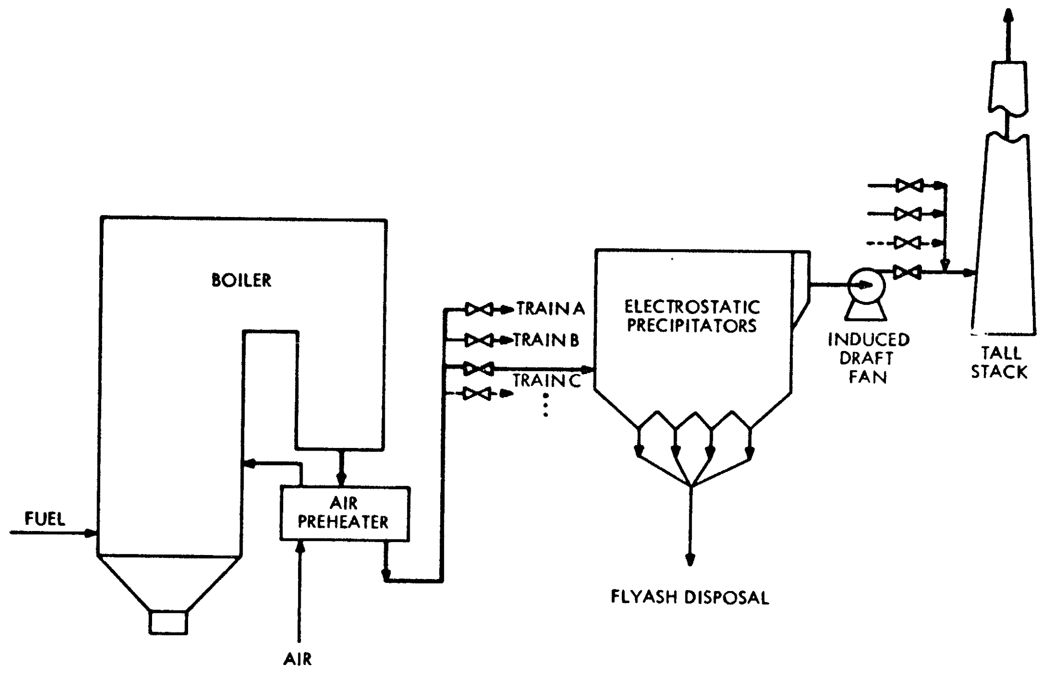
This combination of electrostatic precipitators and a tall stack exerts no control over the emissions of sulfur dioxide. It should be considered a throw away process in that there is no market for the flyash collected, but definite disposal expenses. Sulfur dioxide removal efficiency is zero and particulate removal efficiencies are better than 99%.

System operation is simple, as shown in figure C.4. Flue gas from the boiler is cleaned of most of the particulates while passing through the precipitator, sent through induced draft fans, and exits up the stack. Flyash is removed dry from the precipitators periodically and stored, if land is available, or transported someplace where it can be dumped.

No chemical reactions are involved as the precipitators work on the principles of attraction and repulsion between charged particles. Raw materials are not needed and the rate of flyash production depends only on boiler particulate emissions and precipitator collection efficiencies.

All the processes have been classed as either throw away or byproduct processes and a word of comparison between the two types is valuable. First, it should be noticed that all the abatement methods are at least partially throw away processes since they all attempt to remove particulates. There are few known uses for flyash and none that can consume flyash in the quantities a power plant produces. So all methods face the task of flyash disposal in either wet or dry form.

The main differentiation between throw away and byproduct processes arises when sulfur dioxide control is used. The abatement method can remove the sulfur dioxide by reacting it with materials to produce essentially worthless products. This results in a throw away process and has the advantage of being



Tall Stacks (with Precipitators)

Figure C.4.

a simpler concept to implement, for it does not involve the utility in the operation of a chemical facility. Lower capital costs can result and operating costs are not in any way dependent on the chemical industry market. If the utility must provide a means for disposal of the waste materials, and since these can cause land and water pollution, this problem can be difficult and expensive. In an urban area, with little disposal land available, it may be totally impractical to use a throw away method.

If the abatement method removes the sulfur dioxide by reacting it with materials to produce a valuable product, the process is a byproduct process. This has the advantage of providing revenue from the operation of the abatement device and can help to reduce operating costs significantly. The main problems are that the utility must hire and train personnel to operate the recovery units, the increased system complexity makes its operation less reliable, and finally the revenues depend on the availability and strength of the byproduct market. A utility counting on byproduct revenues to make an abatement process competitive could lose money if the byproduct market became depressed with the introduction of the large quantities of utility byproducts.

APPENDIX D

MODEL COMPUTER PROGRAM

This appendix describes the data requirements of the model and provides a glossary of model variables for identification purposes. It also includes a listing of the model in subroutine form.

Subroutine form was chosen instead of using a main program approach for two reasons. First, the subroutine form was needed to make the model compatible with the generation expansion planning model described in appendix B and reference 35. Second, the one-pass evaluative nature of the model makes repetitive applications necessary if it is desired to examine the sensitivity of results of parameter changes or standards changes. This situation is most easily handled by writing a short main program to vary the quantities of interest and to call the air pollution model. So the subroutine form is the most versatile form for independent model use, and the required form for present supportive use.

Rather than develop two different subroutine forms for independent and supportive uses, it was decided to use the supportive form for both. The differences would arise from the necessity of the subroutine to communicate with the main program in the generation expansion planning program. This communication means that the model necessarily calls some variables in various COMMON blocks which are irrelevant to the air pollution calculations. Such variables are identified in the glossary. When using the program independently, the user's main program must identify the same irrelevant variables in the appropriate COMMON statements, but no values need be assigned.

DATA REQUIREMENTS FOR INDEPENDENT USE

When used independently, the main calling program must define the variables needed by the subroutine model. These variables are grouped into five classes for discussion. The reader is urged to consult reference 35 for more information.

$$\left.\begin{array}{l}\text{1) PSA specification}\\ \text{2) Air pollution standards}\\ \text{3) Meteorological data}\\ \text{4) Program logic controls}\end{array}\right\}\text{-in COMMON}$$

5) Abatement parameters - on file 18.

PSA specification data provides all the plant parameters and specification of site type, background levels, abatement method and whether abatement credits are allowed.

Air pollution standards are in array form to facilitate changes of standards by the generation expansion planning model. The particular standards set used is specified by the variable INDXST which indexes the standards in the model. Ten different sets of standards can be input. Each set contains a limit for sulfur dioxide and particulate emissions and for ground level three hour, twenty-four hour and annual concentrations.

Meteorological data includes the representative annual stability wind rose data for the three physical sites, background levels for all six site alternatives and the representative height of the valley site's valley walls.

Program logic controls are either on or off and regulate printing of output and the inclusion of capital charges and electricity costs by the model.

All of the above variables need only be read into COMMON or defined in DATA statements. The abatement method data must be written onto a random access data file on unit 18. The method in which this is done is critical. Proper format must be followed and the record index, APACOM(2), must be maintained or else the model will never obtain the correct parameters when it searches unit 18.

INPUT DATA VARIABLE EXPLANATIONS

In order to facilitate the user's creation of the appropriate COMMON data, the actual variables which the main program must define are explained. As stated before, the assignment of COMMON variables may be performed in any manner. Abatement method parameters must be stored exactly as directed on file 18 (file 18 also must be created by the user in the main program).

If the generation expansion planning model were used, all the COMMON data would be automatically created and the abatement parameters would be read onto file 18 in the format described below. Thus, the abatement method parameters would have the same input format for the air pollution model and the generation expansion planning program.

1) PSA specification - integer array PID(7), real array SGCF(6), variable DBEFF

PID(1) 7 BCD characters

First two characters - base type

FB - fossil base loaded

FI - fossil intermediate

FP - fossil peaking

GT - gas turbine

CC - combined cycle

Third character - subtype, coal combustion method

C - cyclone firing

G - general firing

Fourth character - not used at present

PID(2) 4 BCD characters - fuel type

First character - base type

C - coal

O - oil

G - gas

Second character - sulfur content

Third character - ash content of coal

H - high

M - medium

L - low

Fourth character - not used at present

PID(3) Integer - plant size in MW

PID(4) Integer - plant startup year

PID(5) 4 BCD characters - site type

First character - thermal pollution site type

Second character - air pollution site type

C - coastal

V - valley

P - plain

Third character - urbanization

U - urban

R - rural

Fourth character - not used at present

PID(6) 4 BCD characters - thermal pollution abatement method

PID(7) 4 BCD characters - air pollution abatement method

First two characters - base type

WL - wet limestone scrubbing

CO - catalytic oxidation

MG - magnesium oxide scrubbing

TS - tall stacks (with precipitators)

Third character - byproduct credits

C - credits

N - no credits

Fourth character - not used at present

SGCF(1) - fuel heat equivalent Btu/ton (coal), Btu/10^3 gal (oil) or Btu/10^6 ft^3 (gas)

SGCF(2) - not used at present

SGCF(3) - not used at present

SGCF(4) - boiler gas flow AMCFM

SGCF(5) - boiler exit gas temperature ^{o}F

SGCF(6) - boiler heat input Btu/hr

DBEFF - boiler efficiency (must be redefined after calling APA)

2) Air pollution standards - real arrays, variable INDXST

PEL(10) - particulate emission limits

SEL(10) - sulfur dioxide emission limits

PGL3M(10) - particulate three hour maximum ground level concentration

SGL3M(10) - sulfur dioxide three hour maximum ground level concentration

PGL24M(10) - particulate twenty-four hour maximum ground level concentration

SGL24M(10) - sulfur dioxide twenty-four hour maximum ground level concentration

PGLA(10) - particulate annual average maximum ground level concentration

SGLA(10) - sulfur dioxide annual average maximum ground level concentration

INDXST - index of standards to be used

3) Meteorological data - real arrays, variable ALT

COAST(80,6) - representative coastal site stability wind rose data

VALLY(80,6) - representative valley site stability wind rose data

PLAIN(80,6) - representative plain site stability wind rose data

Where indices of COAST(I,J) identify:

J = wind speed class (1-6)

I = compass direction by stability class

1-16 sixteen compass directions, stability class A
17-32 sixteen compass directions, stability class B
33-48 sixteen compass directions, stability class C
49-64 sixteen compass directions, stability class D
65-80 sixteen compass directions, stability class E

PBG(6) - particulate background levels

SBG(6) - sulfur dioxide background levels

Where index of PBG(I) identifies:

I=1 Coastal-rural
I=2 Valley-rural
I=3 Plain-rural
I=4 Coastal-urban
I=5 Valley-urban
I=6 Plain-urban

4) Program logic controls - integer arrays. CNTRL(10), APACOM(10)

CNTRL(1) - debug print control 0-no print 1 print

CNTRL(2) - thermal pollution print control	0-no print 1 print
CNTRL(3) - air pollution print control	0-no print 1 print
APACOM(1) - air environmental feasibility	0-infeasible 1 feasible
APACOM(2) - file 18 record index	
APACOM(3) - capital and electricity charges	0-no compute 1 compute
APACOM(4) - stability wind rose print control	0-no print 1 print

5) Abatement method parameters - real variables

Each abatement method requires the four common input parameters cards, followed by input parameter cards for each method. The total numbers of input cards are

WL - 4 common + 2 = 6 cards
CO - 4 common + 2 = 6 cards
MG - 4 common + 4 = 8 cards
TS - 4 common + 1 = 5 cards

The cards of any single process must be read into file 18 sequentially. Index APACOM(2) must be set at the record number of the first record for the abatement method to be used. Since the four common input parameters cards are identical for all the abatement methods, they are only described once. Of course the data would be different.

COMMON INPUT PARAMETERS

Card 1 (6F12.5,8X)

1 SO2EFF	Sulfur dioxide removal efficiency	%
2 PEFF	Particulate removal efficiency	%
3 SGTEMP	Stack gas temperature	°F
4 STREAM	Stream time	hr/yr
5 TRSIZE	Abatement train size	AMCFM
6 DISPAA	Flyash disposal area	acre/100 ton

Card 2 (6F12.5,8X)

1 LABOR	Operating labor	men/shift
2 PMPREQ	Pump and motor power	BHP/train
3 TRAINC	Train cost	$/KW
4 DISPAC	Flyash disposal cost	$/ton
5 CREDAA	System credits	$/KWH, ton 77.7% acid or ton drycake
6 PCTMAT	Maintenance costs	% FCI

Card 3 (6F12.5,8X)

1 STCSTA	Stack cost coefficient a	-
2 STCSTB	Stack cost coefficient b	-
3 STCSTC	Stack cost coefficient c	-
4 CAPCHG	Capital charges	% FCI
5 LABORC	Operating labor cost	$/hr
6 PCTSUP	Supervision cost	% labor

Card 4 (4F12.5,32X)

1	PCTSPY	Plant supplies cost	% maintenance
2	PCTPAY	Payroll overhead cost	% labor + supervision
3	PCTPLT	Plant overhead cost	% labor + supervision + maintenance + supplies
4	ELECTC	Electricity cost	mills/KWH
5	-	(spare)	-
6	-	(spare)	-

WET LIMESTONE SCRUBBING PARAMETERS

Cards 1-4 Common Input Parameters

Card 5 (6F12.5,8X)

1	CACO3	Limestone $CaCO_3$ content	%
2	STOICH	Stoichiometric rate	%
3	CALCHL	Calcination heat loss	MBtu/ton $CaCO_3$
4	DISPAL	Lime products disposal area	acre/100 ton
5	H2OEVP	Pond water loss	lb/hr per acre
6	H2OSCB	Scrubber water loss	lb/hr per train

Card 6 (5F12.5,20X)

1	DPTOTL	Total pressure drop	in H_2O
2	LIMESC	Limestone cost	$/ton
3	DISPLC	Lime products disposal cost	$/ton
4	WATERC	Makeup water cost	$/MGal
5	BOILER	Boiler SO_2 conversion	%
6	-	(spare)	-

CATALYTIC OXIDATION PARAMETERS

Cards 1-4 Common Input Parameters

Card 5 (6F12.5,8X)

1	COTEMP	Entrance gas temperature	^{o}F
2	CATLST	Catalyst loading	ft^3/train
3	CATATT	Catalyst attrition	%/yr
4	H2OEVP	Absorber water consumption	lb/hr
5	H2OCOL	Cooling water use	lb/hr
6	PWRPRC	Precipitation power requirements	KW/train

Card 6 (4F12.5,32X)

1	DPTOTL	Total pressure drop	in H_2O
2	CATALC	Catalyst cost	$\$/\mathrm{ft}^3$
3	WATERC	Makeup water cost	\$/Mgal
4	COOLWC	Cooling water cost	\$/Mgal
5	-	(spare)	-
6	-	(spare)	-

MAGNESIUM OXIDE SCRUBBING PARAMETERS

Cards 1-4 Common Input Parameters

Card 5 (6F12.5,8X)

1 WETCAK	Wetcake water content	%
2 PCT3HY	$MgSO_3 \cdot 3H_2O$ production	%
3 PCTSO4	$MgSO_4 \cdot 7H_2O$ production	%
4 SPYMGO	Initial MgO supply	ton/train
5 MAKEUP	MgO makeup	%/ton SO_2
6 H2OSCB	Scrubber water consumption	lb/hr per train

Card 6 (6F12.5,8X)

1 DRYFUL	Dryer fuel requirements	MBtu/ton wetcake
2 DRYPCT	Dryer heat up stack	%
3 DRYFUC	Dryer fuel costs	$/MBtu
4 DRYASH	Dryer ash emission factor	lb/ton drycake
5 DRYEFF	Dryer ash collection efficiency	%
6 DRYPWR	Dryer power requirements	KW

Card 7 (6F12.5,8X)

1 H2OEVP	Pond water consumption	lb/hr
2 ACIDOS	Acid plant operating share	%
3 ACIDCS	Acid plant investment share	%
4 MGOXIC	MgO cost	$/ton
5 DPTOTL	Total pressure drop	in H_2O
6 ACIDOC	Acid plant operating cost	$/ton drycake

Card 8 (2F12.5,56X)

1	ACIDCC	Acid plant capital cost	M$
2	WATERC	Makeup water cost	$/Mgal
3	-	(spare)	-
4	-	(spare)	-
5	-	(spare)	-
6	-	(spare)	-

TALL STACK PARAMETERS

Cards 1-4 Common Input Parameters

Card 5 (2F12.5,56X)

1	PWRPRC	Precipitator power requirements	KW/train
2	DPTOTL	Total pressure drop	in H_2O
3	-	(spare)	-
4	-	(spare)	-
5	-	(spare)	-
6	-	(spare)	-

GLOSSARY

*indicates an array
+indicates generation expansion program use only

*A	parameters of plume dispersion standard deviation	-
ACCCST	abatement capital cost due to central plant	$
ACIDCC	total central plant capital cost	$
ACIDCS	abatement share of central plant capital cost	$
ACIDOC	central plant operating cost	$/ton crystals
ACIDOS	abatement share of central plant operating cost	%
ACID77	77.7% H_2SO_4 produced	ton/hr
ACOCST	abatement operating costs due to central plant	$/yr
ALT	height of valley walls	m
*APACOM	program logic controls	-
APACST	abatement equipment capital cost	$
AREAL	disposal area for limestone products	acre
AREASH	disposal area for flyash	acre
ARGCON	argument of exponential in concentration calculations	-
ASHHR	flyash production	ton/hr
AVFUEL	plant fuel consumption	ton/hr
+*AWS	generation expansion planning variables	-
+*AWT	generation expansion planning variables	-
*B	parameters of plume dispersion standard deviation	-

BOILER	conversion rate of SO_2 in boiler	%
BYPROD	logic variable regulating byproduct credits	-
*C	parameters of plume dispersion standard deviation	-
CACO3	$CaCO_3$ content of limestone	%
CAMKUP	catalyst makeup required	ft^3/yr
CAOHOH	$Ca(OH)_2$ production	ton/hr
CAPCHG	capital charge rate	%
CAPCST	total capital charges	$/yr
CATALC	catalyst price	$\$/ft^3$
CATATT	catalyst attrition rate	%
CATCST	cost of catalyst makeup	$
CATLOD	catalyst loading	ft^3/train
CATLST	total catalyst used in loading	ft^3
*CNTRL	program logic controls	-
CO	variable for testing PSA specifications	-
COAL	variable for testing PSA specifications	-
*COAST	coastal site stability wind rose data	%
COAST1	variable for testing PSA specification	-
COLCST	cost of cooling water	$/yr
*CONC	concentration factor matrix	-
COOLWC	price of cooling water	$/Mgal
COTEMP	catalyst operating temperature	^oF
CRED	total abatement process credits	$
CREDAA	abatement process credit rate	$/(·)
CREDIT	variable for testing PSA specifications	-

CRSDRY	hydrated crystal production	ton/hr
CRSWET	wetcake production	ton/hr
CSTAAB	total abatement capital cost	$
+CSTTAB	generation expansion planning variable	-
+CTR	generation expansion planning variable	-
CYCLON	variable for testing PSA specifications	-
+*DB	generation expansion planning variable	-
DBEFF	boiler efficiency/or boiler efficiency change	%
DELTAH	plume rise	m
*DIR	output literal direction titles	-
DISPAA	flyash disposal area factor	acre/100 ton-yr
DISPAC	flyash disposal price	$/ton
DISPAL	limestone products disposal area factor	acre/100 ton-yr
DISPLC	limestone products disposal price	$/ton
DIST	downwind distance	m
+*DP	generation expansion planning variables	-
DPTOTL	total pressure drop	in H_2O
DRYASH	dryer emission factor	%
DRYBTU	dryer heat consumption	MBtu/ton wetcake
DRYCAK	anhydrous crystal production	ton/hr
DRYCST	dryer fuel cost	$/yr
DRYEFF	dryer dust removal efficiency	%
DRYFUC	dryer fuel price	$/MBtu
DRYFUL	dryer fuel used	MBtu

DRYPCT	dryer heat going to stack	%
DRYPWR	dryer electric consumption	KW
DSACST	flyash disposal cost	$/yr
DSLCST	limestone products disposal cost	$/yr
ELECHR	abatement electric power	KWH
ELECST	electricity cost	$/yr
ELECTC	electricity price	mills/KWH
F	buoyancy flux	m^4/s^3
FB	variable for testing PSA specification	-
FI	variable for testing PSA specification	-
FLYASH	boiler flyash production	ton/hr
+FOCTA	generation expansion planning variable	-
FOCAA	total capacity factor adjusted fixed operating costs	$/100 yr
FP	variable for testing PSA specification	-
*FREQ1	frequency matrix of coastal stability wind rose data	%
*FREQ2	frequency matrix of valley stability wind rose data	%
*FREQ3	frequency matrix of plain stability wind rose data	%
GAS	variable for testing PSA specifications	-
GASFLO	actual gas flow in abatement equipment	ACFM
GEN	variable for testing PSA specifications	-
*GLCONP	particulate ground level concentration matrix	$\mu g/m^3$

*GLCONS	sulfur dioxide ground level concentration matrix	$\mu g/m^3$
GLMULT	ground level concentration multiplier matrix	-
GT	variable for testing PSA specifications	-
HALF	-0.5	-
*HEF	effective stack heights	m
HEF3M	limited mixing layer	m
HIGH	variable for testing PSA specifications	-
*HT	stack height options	m
H2OCAO	water consumption by CaO hydration	lb/hr
H2OCOL	cooling water use	lb/hr
H2OCST	process water cost	$/yr
H2OEVP	pond evaporation loss	lb/hr
H2OSCB	scrubber evaporation loss	lb/hr
I	loop parameter	-
III	output parameter	-
*ID	output PSA specification variable	-
IDAPAM	air pollution abatement method index	-
IDBGRD	background level index	-
IDFUEL	fuel type index	-
IDGAST	gas turbine evaluation identification	-
IDSITE	site type index	-
IID	loop parameter	-
INDXST	air pollution standards index	-
J	loop parameter	-

JID	loop parameter	-
K	loop parameter	-
L	loop parameter	-
LABCST	labor cost	\$/yr
LABOR	operational labor	men
LABORC	operational labor wages	\$/hr
LIMCST	limestone cost	\$/yr
LIMEHR	limestone consumption	ton/hr
LIMEP	limestone particulate emissions	ton/hr
LIMESC	limestone price	\$/ton
LIMPHR	limestone solids production	ton/hr
LOW	variable for testing PSA specifications	-
M	loop variable	-
MAKEUP	magnesium oxide makeup rate	%/ton SO_2 removed
MATCST	maintenance costs	\$/yr
MED	variable for testing PSA specifications	-
MG	variable for testing PSA specifications	-
MGMKUP	magnesium oxide makeup	ton/hr
MGOCST	magnesium oxide makeup cost	\$/yr
MGOXIC	magnesium oxide price	\$/ton
N	loop parameter	-
NOCRED	variable for testing PSA specifications	-
NUMDIS	number of downwind distances examined	-
NUMHT	number of stack heights available	-
OIL	variable for testing PSA specifications	-

PAYCST	payroll overhead cost	$/yr
*PBG	particulate background levels	µg/m^3
PCTACH	high ash content	%
PCTACL	low ash content	%
PCTACM	medium ash content	%
PCTMAT	maintenance cost rate	%
PCTPAY	payroll overhead rate	%
PCTPLT	plant overhead rate	%
PCTSCH	high coal sulfur content	%
PCTSCL	low coal sulfur content	%
PCTSCM	medium coal sulfur content	%
PCTSOH	high oil sulfur content	%
PCTSOL	low oil sulfur content	%
PCTSOM	medium oil sulfur content	%
PCTSO4	conversion of SO_2 to $MgSO_4 \cdot 7H_2O$	%
PCTSPY	plant supplies rate	%
PCTSUL	fuel sulfur content	%
PCTSUP	supervision rate	%
PCT3HY	conversion of SO_2 to $MgSO_3 \cdot 3H_2O$	%
PEF	particulate emission factor	lb/ton
PEFF	particulate removal efficiency	%
*PEL	particulate emission limits	g/10^6 cal
PEMB	particulate boiler emissions	g/s
PEMS	particulate stack emissions	g/s
PERCAL	emissions conversion factor	-
PERP	adjusted particulate stack emissions	g/10^6 cal

PERSO2	adjusted sulfur dioxide stack emissions	$g/10^6$ cal
*PGLA	particulate annual air quality standard	$\mu g/m^3$
PGLAN	maximum particulate annual ground level concentration	$\mu g/m^3$
PGL1	maximum particulate ground level one hour concentration	$\mu g/m^3$
PGL3	maximum particulate ground level three hour concentration	$\mu g/m^3$
*PGL3M	particulate three hour air quality standard	$\mu g/m^3$
PGL24	maximum particulate twenty-four hour ground level concentration	$\mu g/m^3$
*PGL24M	particulate twenty-four hour air quality standard	$\mu g/m^3$
*PID	PSA specification variables	-
*PLAIN	plain site stability wind rose data	%
PLAIN1	variable for testing PSA specifications	-
PLTCST	plant supplies cost	$/yr
PMPPWR	pump and motor electricity consumption	KW
PMPREQ	pump and motor requirements	BHP
POHCST	plant overhead cost	$/yr
+POWRTA	generation expansion planning variable	-
POWRAA	total electric power consumption	KW-MW
POWRPA	generation expansion planning variable	-
PWRPRC	precipitator electricity consumption	-
+QR	generation expansion planning variable	-

QH	stack heat emission	Btu/hr
RN	file 18 record variable	-
*RRA	air pollution resource requirements	GPS, acres
+*RRP	generation expansion planning variable	-
+*RRT	generation expansion planning variable	-
RURAL	variable for testing PSA specifications	-
*SBG	sulfur dioxide background levels	$\mu g/m^3$
*SEL	sulfur dioxide emission limits	$g/10^6$ cal
*SGCF	plant description parameters	-
*SGLA	sulfur dioxide annual air quality standards	$\mu g/m^3$
SGLAN	maximum sulfur dioxide annual ground level concentration	$\mu g/m^3$
SGL1	maximum sulfur dioxide ground level one hour concentration	$\mu g/m^3$
SGL3	maximum sulfur dioxide ground level three hour concentration	$\mu g/m^3$
*SGL3M	sulfur dioxide three hour air quality standards	$\mu g/m^3$
SGL24	maximum sulfur dioxide twenty-four hour ground level concentration	$\mu g/m^3$
*SGL24M	sulfur dioxide twenty-four hour air quality standards	$\mu g/m^3$
SGTEMP	stack gas temperature	°F
*SMZ	generation expansion planning variable	-
SO2EF	sulfur dioxide emission factor	lb/ton

SO2EFF	sulfur dioxide removal efficiency	%
SO2EMB	sulfur dioxide boiler emissions	g/s
SO2EMS	sulfur dioxide stack emissions	g/s
SO2REM	sulfur dioxide removed	ton/hr
SPYMGO	magnesium oxide supply	ton/train
+ST	generation expansion planning variable	-
STAB	output literal stability class titles	-
STACK	stack height	m
STCSTA	stack cost parameter	-
STCSTB	stack cost parameter	-
STCSTC	stack cost parameter	-
STKCST	stack cost	$
STOICH	stoichiometric rate of $CaCO_3$ addition	%
STREAM	abatement operating hours	hr/yr
SUPCST	supervision cost	$/yr
TA	ambient temperatures	°F
TEMP	temporary storage for sorting	-
+TIME	generation expansion planning variable	-
+TIN	generation expansion planning variable	-
+TMAX	generation expansion planning variable	-
+*TPACOM	generation expansion planning variable	-
+TR	generation expansion planning variable	-
TRAIN	number of trains	-
TRAINC	cost of train equipment	$/KW
TRSIZE	train capacity	AMCFM

TS	variable for testing PSA specifications	-
URBAN	variable for testing PSA specifications	-
*VALLY	valley site stability wind rose data	%
VALLY1	variable for testing PSA specifications	-
WATERC	process water price	$/Mgal
WETCAK	crystal surface water content	%
*WIND	representative wind speeds	m/s
WL	variable for testing PSA specifications	-
*X	downwind distances	m
XMMD	downwind distance to initial total mixing	m

PROGRAM LISTING

The following is a listing of the subroutine air pollution model. There are included some error and communication statements using file 15 and a timing routine WHEN(·) for the generation expansion planning program. The user should remove these for independent use of the model or include JCL cards for file 15 and include the timing routine. Gas turbine related cards are identified by *GAS* and generation expansion planning program communication cards and error cards are identified by *GENX*.

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0001                 SUBROUTINE APA
                C
                C SUBROUTINE APA CALCULATES THE STACK EMISSIONS AND GROUND LEVEL
                C CONCENTRATIONS OF SO2 AND PARTICULATES CAUSED BY THE PLANT.
                C THESE ARE TESTED AGAINST THE AIR POLLUTION STANDARDS IN EFFECT.
                C IF THE PLANT MEETS ALL THE AIR POLLUTION STANDARDS, THE ECONOMICS OF
                C THE PLANT ABATEMENT DEVICE ARE DETERMINED.
                C
0002                 INTEGER TIME(5),PID,ST,CNTRL,TPACOM,APACOM,RN
0003                 REAL  LABOR ,LABORC,LIMESC,LABCST,MATCST,LIMCST,LIMPHR,LIMEHR,LIMP
                    1,MAKEUP,MGOCST,MGOXIC
0004                 COMMON /RNRNRN/ RN
0005                 COMMON /PID/PID(7)
0006                 COMMON /PLAC/INDXST,ST(10),TR(10),TMAX(10),SMZ(10),APL(10),SEL(10)
                    1,SGLA(10),SGL24M(10),SGL3M(10),PEL(10),PGLA(10),PGL24M(10),PGL3M(1
                    20),DB(10),WB(10),DP(10),AWS(10),AWT(10)
0007                 COMMON /SGCF/SGCF(6)
0008                 COMMON /CABC/QR,CTR,TIN,DBEFF
0009                 COMMON/CPR/CSTTAB,CSTAAB,FOCTA,VOCTA,FOCAA,VOCAA,POWRTA,POWRAA,POW
                    1RPA,RRT(4),RRA(4),RRP(4)
0010                 COMMON /CNTRL/CNTRL(10),TPACOM(10),APACOM(10)
0011                 COMMON /SMD/COAST(80,6),VALLY(80,6),PLAIN(80,6),SBG(6),PBG(6),ALT
0012                 INTEGER*4  ID(5),FP,FI,FB,GT,CC,OIL,COAL,GAS,HIGH,MED,LOW,COAST1,V
                    1ALLY1,PLAIN1,RURAL,URBAN,WL,CO,MG,TS,CREDIT,NOCRED,CYCLON,GEN
0013                 DIMENSION  DIR(16),FREQ1(16,30),FREQ2(16,30),FREQ3(16,30),WIND(6),
                    1STAB(5),A(7),B(7),C(7),HT(10),X(10),HEF(10),CONC(30,10),GLMULT(10,
                    230),GLCONS(10,30),GLCONP(10,30)
0014                 DATA WIND,A,B,C/0.77,2.57,4.38,6.95,9.78,13.1,0.001,0.048,0.119,2.
                    1610,0.105,0.187,  11.61,1.890,1.110,0.915,0.450,0.771,0.755,0.266,
                    29.6,2.0,0.0,-25.5,0.0,-1.4,-54.7/
0015                 DATA  PCTSOH,PCTSOM,PCTSOL,PCTSCH,PCTSCM,PCTSCL,PCTACH,PCTACM,PCTA
                    1CL/2.5,1.5,0.5,4.5,3.0,1.0,25.0,15.0,5.0/
0016                 DATA  X,NUMDIS/1000.,2000.,3000.,5000.,7000.,10000.,15000.,30000.,
                    150000.,70000.,10/
0017                 DATA  HT,NUMHT/100.,125.,150.,175.,200.,225.,250.,275.,300.,350.,1
                    10/
0018                 DATA  TA/60./
0019                 DATA  FP,FI,FB,GT,CC,OIL,COAL,GAS,HIGH,MED,LOW,COAST1,VALLY1,PLAIN
                    11,RURAL,URBAN,WL,CO,MG,TS,CREDIT,NOCRED,CYCLON,GEN/'FP  ','FI  ','
                    2FB  ','GT  ','CC  ','O   ','C   ','G   ','H   ','M   ','L   ','C
                    3 ','V   ','P   ','R   ','U   ','WL  ','CO  ','MG  ','TS  ','C   ',
                    4'N   ','C   ','G   '/
0020                 DATA DIR,STAB/'N','NNE','NE','ENE','E','ESE','SE','SSE','S','SSW',
                    1'SW','WSW','W','WNW','NW','NNW','A','B','C','D','E'/
                C
                C FUNCTION  FTOC CHANGES FAHRENHEIT TO CENTIGRADE.
0021                 FTOC(A)=0.55555555*(A-32.)
0022                 PLSIZE=PID(3)
0023                 RN=APACOM(2)
                C
                C CREATE FREQUENCY MATRICES WITH THE STABILITY WIND ROSE DATA.
0024                 DO 500 I=1,16
0025                 DO 500 K=1,5
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            DO 500 N=1,6
            M=(K-1)*16+I
            J=(K-1)*6 +N
            FREQ1(I,J)=COAST(M,N)
            FREQ2(I,J)=VALLY(M,N)
        500 FREQ3(I,J)=PLAIN(M,N)
      C
      C TEST PLANT ID TO DETERMINE PLANT TYPE, FUEL TYPE AND COMBUSTION
      C METHOD.  ASSIGN SULFUR AND ASH CONTENTS AND ASSIGN SO2 AND
      C PARTICULATE EMISSION FACTORS.
            HIGH=ILS(IRS(HIGH,24),24)
            MED=ILS(IRS(MED,24),24)
            LOW=ILS(IRS(LOW,24),24)
            IF(IRS(PID(1),16).EQ.IRS(FP,16))  GO TO 205
            IF(IRS(PID(1),16).EQ.IRS(FI,16))  GO TO 205
            IF(IRS(PID(1),16).EQ.IRS(FB,16))  GO TO 205
            IF(IRS(PID(1),16).EQ.IRS(GT,16))  GO TO 100                    *GAS*
            IF(IRS(PID(1),16).EQ.IRS(CC,16))  GO TO 100                    *GAS*
            CALL WHEN(TIME)                                               *GENX*
            WRITE(15,751)(TIME(I),I=3,5),PID(1)                           *GENX*
            GO TO 1000
        100 IDGAST=1                                                       *GAS*
            CALL WHEN(TIME)                                               *GENX*
            WRITE(15,701)(TIME(I),I=3,5),PID(1)                           *GENX*
        205 IF(IRS(PID(2),24).EQ.IRS(OIL, 24)) IDFUEL=1
            IF(IRS(PID(2),24).EQ.IRS(COAL,24)) IDFUEL=2
            IF(IRS(PID(2),24).EQ.IRS(GAS, 24)) IDFUEL=3
            IF(IDGAST.EQ.1) GO TO (211,105,110),IDFUEL                     *GAS*
            GO TO (210,215,230),  IDFUEL
        105 APACOM(1)=0                                                    *GAS*
            CALL WHEN(TIME)                                               *GENX*
            WRITE(15,752)(TIME(I),I=3,5),PID(2)                           *GENX*
            GO TO 150                                                      *GAS*
        110 PCTSUL=1.                                                      *GAS*
            PCTASH=1.                                                      *GAS*
            SO2EF =0.6                                                     *GAS*
            PEF   =7.5                                                     *GAS*
            GO TO 250                                                      *GAS*
        210 SO2EF=159.
            PEF=8.0
        211 IF(ILS(IRS(PID(2),16),24).EQ.HIGH) PCTSUL=PCTSOH
            IF(ILS(IRS(PID(2),16),24).EQ.MED ) PCTSUL=PCTSOM
            IF(ILS(IRS(PID(2),16),24).EQ.LOW ) PCTSUL=PCTSOL
            IF(IDGAST.EQ.1)  GO TO 115                                     *GAS*
            GO TO 235
        115 IF(PCTSUL.NE.PCTSOL)  GO TO 120                                *GAS*
            PCTASH=1.                                                      *GAS*
            SO2EF =142.                                                    *GAS*
            PEF   =15.                                                     *GAS*
            GO TO 250                                                      *GAS*
        120 APACOM(1)=0                                                    *GAS*
            CALL WHEN(TIME)                                               *GENX*
            WRITE(15,753)(TIME(I),I=3,5),PID(2)                           *GENX*
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0075                  GO TO 150                                                              *GAS*
0076             215  SO2EF=38.
0077                  IF(ILS(IRS(PID(2),16),24).EQ.HIGH) PCTSUL=PCTSCH
0078                  IF(ILS(IRS(PID(2),16),24).EQ.MED ) PCTSUL=PCTSCM
0079                  IF(ILS(IRS(PID(2),16),24).EQ.LOW ) PCTSUL=PCTSCL
0080                  IF(ILS(IRS(PID(1),8 ),24).EQ.ILS(IRS(CYCLON,24),24)) GO TO 220
0081                  IF(ILS(IRS(PID(1),8 ),24).EQ.ILS(IRS(GEN   ,24),24)) GO TO 225
0082                  CALL WHEN(TIME)                                                        *GENX*
0083                  WRITE(15,754)(TIME(I),I=3,5),PID(2),PID(1)                             *GENX*
0084             220  PEF=2.
0085                  GO TO 235
0086             225  PEF=16.
0087                  GO TO 235
0088             230  SO2EF =0.6
0089                  PEF=15.
0090                  PCTSUL=1.0
0091             235  IF(IDFUEL.EQ.2)    GO TO  245
0092             240  PCTASH=1.
0093                  GO TO 250
0094             245  IF(ILS(IRS(PID(2), 8),24).EQ.HIGH) PCTASH=PCTACH
0095                  IF(ILS(IRS(PID(2), 8),24).EQ.MED ) PCTASH=PCTACM
0096                  IF(ILS(IRS(PID(2), 8),24).EQ.LOW ) PCTASH=PCTACL
                C
                C TEST PLANT ID FOR SITE TYPE AND ASSIGN BACKGROUND LEVEL ID.
                C ALSO TEST PLANT ID FOR ABATEMENT METHOD AND BYPRODUCT CREDITS.
0097             250  IF(ILS(IRS(PID(5),16),24).EQ.ILS(IRS(COAST1,24),24)) IDSITE=1
0098                  IF(ILS(IRS(PID(5),16),24).EQ.ILS(IRS(VALLY1,24),24)) IDSITE=2
0099                  IF(ILS(IRS(PID(5),16),24).EQ.ILS(IRS(PLAIN1,24),24)) IDSITE=3
0100                  IF(ILS(IRS(PID(5),8 ),24).EQ.ILS(IRS(URBAN ,24),24)) IDBGRD=2*IDSI
                     1TE
0101                  IF(ILS(IRS(PID(5),8 ),24).EQ.ILS(IRS(RURAL ,24),24)) IDBGRD=IDSITE
0102                  IF(ILS(IRS(PID(7),8 ),24).EQ.ILS(IRS(CREDIT,24),24)) BYPROD=1.0
0103                  IF(ILS(IRS(PID(7),8 ),24).EQ.ILS(IRS(NOCRED,24),24)) BYPROD=0.0
0104                  IF(IDGAST.EQ.1)  IDAPAM=5                                              *GAS*
0105                  IF(IDGAST.EQ.1)  GO TO 251                                             *GAS*
0106                  IF(IRS(PID(7),16).EQ.IRS(WL,16))   IDAPAM= 1
0107                  IF(IRS(PID(7),16).EQ.IRS(CO,16))   IDAPAM= 2
0108                  IF(IRS(PID(7),16).EQ.IRS(MG,16))   IDAPAM= 3
0109                  IF(IRS(PID(7),16).EQ.IRS(TS,16))   IDAPAM= 4
                C
                C READ GENERAL ABATEMENT METHOD PARAMETERS FROM FILE 18.
0110                  RN=APACOM(2)
0111                  READ(18'RN, 6)      SO2EFF,PEFF   ,SGTEMP,STREAM,TRSIZE,DISPAA          COM 1
0112                  READ(18'RN, 6)      LABOR ,PMPREQ,TRAINC,DISPAC,CREDAA,PCTMAT          COM 2
0113                  READ(18'RN, 6)      STCSTA,STCSTB,STCSTC,CAPCHG,LABORC,PCTSUP          COM 3
0114                  READ(18'RN, 4)      PCTSPY,PCTPAY,PCTPLT,ELECTC                        COM 4
0115                  IF(IDAPAM.EQ.4)  SGTEMP=SGCF(5)
                C
                C CALCULATE SO2 EMISSIONS AND REMOVAL RATES, AND PARTICULATE
                C EMISSIONS.
0116             251  AVFUEL=SGCF(6)/SGCF(1)
0117                  SO2EMB=AVFUEL*SO2EF*PCTSUL*0.126111111
0118                  SO2REM=AVFUEL*SO2EF *PCTSUL*SO2EFF/100.
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      FLYASH=AVFUEL*PEF*PCTASH
      PEMB  =FLYASH*0.12611111
C
C IF WET LIMESTONE SCRUBBING IS USED, ADJUST PARTICULATE EMISSION
C RATE TO INCLUDE LIMESTONE EMISSIONS FROM BOILER.  READ
C THE NECESSARY PARAMETERS FROM FILE 18.
      IF(IDAPAM.NE.1)    GO TO 252
      READ(18'RN, 6)     CACO3 ,STOICH,CALCHL,DISPAL,H2OEVP,H2OSCB          WL  5
      READ(18'RN, 5)     DPTOTL,LIMESC,DISPLC,WATERC,BOILER                 WL  6
      LIMEHR=AVFUEL*SO2EF *PCTSUL*STOICH*100./(CACO3 *64.*2000.)
      LIMEP=((100.-CACO3 )*LIMEHR*2000./100. + 136.*AVFUEL*SO2EF *PCTSUL
     1*BOILER/(64.*100.))*PEF/20.
      PEMB  =PEMB  +LIMEP *0.12611111
C
C PRINT OUT PLANT DESCRIPTION, BOILER EMISSIONS AND STABILITY
C WIND ROSE DATA FOR THE SITE USED.
  252 ID(1)=ILS(IRS(PID(1), 8), 8)
      ID(2)=ILS(IRS(PID(2),24),24)
      ID(3)=ILS(IRS(PID(3),16),24)
      ID(4)=ILS(IRS(PID(5), 8),24)
      ID(5)=ILS(IPS(PID(7),16),16)
      IF(IDGAST.EQ.1)  ID(5)=PID(1)                                        *GAS*
      IF(APACOM(4).NE.1)  GO TO 270
      CALL WHEN(TIME)                                                     *GENX*
      WRITE(15,702)(TIME(I),I=3,5),PID(5)                                 *GENX*
      DO 504 K=1,5
      WRITE(6,924) STAB(K)
      DO 504 I=1,16
      N=(K-1)*16+I
      GO TO (255,260,265),  IDSITE
  255 WRITE(6,995)  STAB(K),DIR(I),(COAST(N,J),J=1, 6)
      GO TO 504
  260 WRITE(6,995)  STAB(K),DIR(I),(VALLY(N,J),J=1, 6)
      GO TO 504
  265 WRITE(6,995)  STAB(K),DIR(I),(PLAIN(N,J),J=1, 6)
  504 CONTINUE
  270 IF(CNTRL(3).EQ.1)  WRITE(6,815)    (PID(I),I=1,7),ID(1),ID(3),ID(2)
     1,SO2EF,SO2EMB,PID(3),ID(4),PCTSUL,PEF,PEMB,PID(4),ID(5),PCTASH,BYP
     2ROD,AVFUEL
C
C CALCULATE STACK EMISSIONS PER MILLION CALORIES OF HEAT INPUT.
      SO2EMS=(100.-SO2EFF)*SO2EMB/100.
      PEMS=(100.-PEFF)*PEMB/100.
      PERCAL=3.6E+9/(251.83*SGCF(6))
C
C IF MAGNESIUM OXIDE SCRUBBING IS USED,ADJUST PARTICULATE EMISSIONS
C TO INCLUDE DUST EMISSIONS FROM THE WETCAKE DRYER.
      IF(IDAPAM.NE.3)    GO TO 271
      READ(18'RN, 6)     WETCAK,PCT3HY,PCTSO4,SPYMGO,MAKEUP,H2OSCB          MG  5
      READ(18'RN, 6)     DRYFUL,DRYPCT,DRYFUC,DRYASH,DRYEFF,DRYPWR          MG  6
      DRYCAK=SO2REM*(PCTSO4*120.+(100.-PCTSO4)*104.)/(200000.*64.)
      CRSWET=SO2REM*(PCT3HY*158.+PCTSO4*246.+(100.-PCT3HY-PCTSO4)*212.)/
     1(64.*200000.)*100./(100.-WETCAK)
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0156                    PEMS  =PEMS   +DRYASH*DRYCAK*(100.-DRYEFF)*0.12611111/100.
0157                271 PERSO2=SO2EMS*PERCAL
0158                    PERP  =PEMS   *PERCAL
                  C
                  C TEST STACK EMISSIONS AGAINST STANDARDS.  IF PLANT FAILS,
                  C PRINT RESULTS AND TERMINATE PROGRAM.  OTHERWISE, CONTINUE.
0159                    IF(PERSO2.GT.SEL(INDXST))   GO TO 275
0160                    IF(PERP  .GT.PEL(INDXST))   GO TO 275
0161                    GO TO 300
0162                275 APACOM(1)=0
0163                    CALL WHEN(TIME)                                                  *GENX*
0164                    IF(CNTRL(3).NE.1)  WRITE(15,703) (TIME(III),III=3,5),(PID(IIM),IIM  *GENX*
                       1=1,7)                                                            *GENX*
0165                    IF(CNTRL(3).EQ.1)  WRITE(6,820)
0166                    IF(CNTRL(3).EQ.1)  WRITE(6,900)
0167                    IF(CNTRL(3).EQ.1)  WRITE(6,825)   PERSO2,SEL(INDXST),PERP,PEL(INDX
                       1ST)
                        GO TO 1000
                  C
                  C CALCULATE BUOYANCY FLUX OF STACK GAS.
0168                300 QH=((100.-DBEFF)/100.)*SGCF(6)*(FTOC(SGTEMP-TA))/FTOC(SGCF(5)-TA)
0169                    IF(IDAPAM.EQ.3)  QH=QH+DRYFUL*CRSWET*DRYPCT*1.E+6/100.
0170                    F=2.65822E-6*QH
0171                    HALF=-0.5
                  C
                  C INITIALIZE STACK HEIGHT LOOP.  CALCULATE WORST CASE LIMITED
                  C MIXING LAYER, THE DOWNWIND DISTANCE OF MAXIMUM CONCENTRATIONS, AND
                  C THE WORST CASE THREE HOUR GROUND LEVEL CONCENTRATIONS .
0172                    DO 515 K=1,NUMHT
0173                    STACK=HT(K)
0174                    IF(IDGAST.EQ.1)  STACK=HT(K)/5.                                  *GAS*
0175                    HEF3M =STACK+1.6*F**0.33333334*(10.*STACK)**0.66666667/5.0
0176                    IF((IDSITE.EQ.2).AND.(HEF3M .LE.ALT    ))  HEF3M =HEF3M -ALT    /2.
0177                    IF((IDSITE.EQ.2).AND.(HEF3M .GT.ALT))  HEF3M =HEF3M/2.
0178                    XMMD=2.*EXP((1./B(2))*ALOG((0.47*HEF3M-C(2))/A(2)))
0179                    SGL3  =1.E+6*SO2EMS/(0.39269908*HEF3M *5.0*XMMD  )
0180                    PGL3  =1.E+6*PEMS  /(0.39269908*HEF3M *5.0*XMMD  )
                  C
                  C TEST WORST CASE THREE HOUR GROUND LEVEL CONCENTRATIONS AGAINST AIR
                  C QUALITY STANDARDS. IF PLANT FAILS AND STACK HEIGHT LOOP IS COMPLETED,
                  C PRINT THE RESULTS AND TERMINATE.  OTHERWISE, INCREMENT STACK HEIGHT
                  C LOOP AND REPEAT CALCULATIONS.
                  C IF PLANT PASSES, CONTINUE.
0181                    IF(SGL3  .GT.(SGL3M (INDXST)-SBG(IDBGRD)))   GO TO 305
0182                    IF(PGL3  .GT.(PGL3M (INDXST)-PBG(IDBGRD)))   GO TO 305
0183                    GO TO 310
0184                305 IF(K.LT.NUMHT)   GO TO 515
0185                    APACOM(1)=0
0186                    CALL WHEN(TIME)                                                  *GENX*
0187                    IF(CNTRL(3).NE.1)  WRITE(15,704) (TIME(III),III=3,5),(PID(IIM),IIM  *GENX*
                       1=1,7)                                                            *GENX*
0188                    IF(CNTRL(3).EQ.1)  WRITE(6,830)
0189                    IF(CNTRL(3).EQ.1)  WRITE(6,900)
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0190              IF(CNTRL(3).EQ.1)  WRITE(6,825)    PERSO2,SEL(INDXST),PERP,PEL(INDX
                 1ST)
0191              IF(CNTRL(3).EQ.1)  WRITE(6,835)    SGL3,SGL3M(INDXST),PGL3,PGL3M(IN
                 1DXST)
0192              IF(CNTRL(3).EQ.1)  WRITE(6,836)    HEF3M,XMMD,STACK,SBG(IDBGRD),PBG
                 1(IDBGRD)
0193              IF((CNTRL(3).EQ.1).AND.(IDSITE.EQ.2))    WRITE(6,837)   ALT
0194              GO TO 1000
            C
            C CALCULATE WORST CASE TWENTY-FOUR HOUR GROUND LEVEL CONCENTRATIONS
            C FROM THREE HOUR WORST CASE.
0195          310 SGL1=1.2457309*SGL3
                  PGL1=1.2457309*PGL3
0196              SGL24=0.25*SGL1
0197              PGL24=0.25*PGL1
0198
            C
            C TEST WORST CASE TWENTY-FOUR HOUR GROUND LEVEL CONCENTRATIONS AGAINST
            C AIR QUALITY STANDARDS.  IF PLANT FAILS AND STACK HEIGHT LOOP IS
            C COMPLETED, PRINT THE RESULTS AND TERMINATE. OTHERWISE, INCREMENT
            C STACK HEIGHT AND REPEAT CALCULATIONS.
            C IF PLANT PASSES, CONTINUE.
0199              IF(SGL24 .GT.(SGL24M(INDXST)-SBG(IDBGRD)))    GO TO 315
0200              IF(PGL24 .GT.(PGL24M(INDXST)-PBG(IDBGRD)))    GO TO 315
0201              GO TO 320
0202          315 IF(K.LT.NUMHT)    GO TO 515
0203              APACCM(1)=0                                                      *GENX*
0204              CALL WHEN(TIME)                                                  *GENX*
0205              IF(CNTRL(3).NE.1)  WRITE(15,705) (TIME(III),III=3,5),(PID(IIM),IIM  *GENX*
                 1=1,7)
0206              IF(CNTRL(3).EQ.1)  WRITE(6,840)
0207              IF(CNTRL(3).EQ.1)  WRITE(6,900)
0208              IF(CNTRL(3).EQ.1)  WRITE(6,825)    PERSO2,SEL(INDXST),PERP,PEL(INDX
                 1ST)
0209              IF(CNTRL(3).EQ.1)  WRITE(6,835)    SGL3,SGL3M(INDXST),PGL3,PGL3M(IN
                 1DXST)
0210              IF(CNTRL(3).EQ.1)  WRITE(6,845)    SGL24,SGL24M(INDXST),PGL24,PGL24
                 1M(INDXST)
0211              IF(CNTRL(3).EQ.1)  WRITE(6,836)    HEF3M,XMMD,STACK,SBG(IDBGRD),PBG
                 1(IDBGRD)
0212              IF((CNTRL(3).EQ.1).AND.(IDSITE.EQ.2))    WRITE(6,837)   ALT
0213              GO TO 1000
            C
            C INITIALIZE STABILITY CLASS LOOP, WIND SPEED LOOP AND DOWNWIND DISTANCE
            C LOOP.  CALCULATE PLUME RISE AND EFFECTIVE STACK HEIGHT.  INCLUDE
            C VALLEY EFFECTS IF VALLEY IS USED AS SITE.
0214          320 DO 510 J=1,5
0215              DO 510 I=1,6
0216              M=(J-1)*6+I
0217              IF(J.EQ.5)  DELTAH=2.9*((F/(WIND(I)*(9.8/FTOC,TA)*(10.0+9.8))))**0
                 1.33333334)
0218              DO 505 L=1,NUMDIS
0219              DIST  =X(L)
0220              IF(IDGAST.EQ.1)  DIST  =X(L)/10.                                 *GAS*
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      IF(J.EQ.5)  GO TO 335
      IF(DIST.GE.(10.*STACK))    GO TO 330
  325 DELTAH=1.6*F**0.33333334*DIST**0.66666667/WIND(I)
      GO TO 335
  330 DELTAH=1.6*F**0.33333334*((10.*STACK)**0.66666667)/WIND(I)
  335 HEF(K)=DELTAH+STACK
      IF((IDSITE.EQ.2).AND.(HEF(K).LE.ALT))  HEF(K)=HEF(K)-ALT/2.
      IF((IDSITE.EQ.2).AND.(HEF(K).GT.ALT))  HEF(K)=HEF(K)/2.
C
C CALCULATE ELEMENTS OF CONCENTRATION FACTOR MATRIX.
      SIGMAZ=A(J)*X(L)**B(J)+C(J)
      IF((J.EQ.4).AND.(DIST.GT.1000.))  SIGMAZ=A(6)*DIST**B(6)+C(6)
      IF((J.EQ.5).AND.(DIST.GT.1000.))  SIGMAZ=A(7)*DIST**B(7)+C(7)
      ARGCON=(HALF*HEF(K)*HEF(K)/(SIGMAZ*SIGMAZ))
      IF(ARGCON.LE.-80.)  ARGCON=-80.
      CONC(M,L)=2.0E+6*EXP(ARGCON)/(WIND(I)*SIGMAZ*0.9843506*DIST)
  505 CONTINUE
  510 CONTINUE
C
C MATRIX MULTIPLY THE FREQUENCY AND CONCENTRATION MATRICES TO
C GET THE GROUND LEVEL CONCENTRATION MULTIPLIER MATIX.  SCALAR MULTIPLY
C TO GET GROUND LEVEL CONCENTRATION MATRICES OF SO2 AND PARTICULATES.
      GO TO (340,345,350), IDSITE
  340 CALL  GMPRD(FREQ1,CONC,GLMULT,16,30,NUMDIS)
      GO TO 355
  345 CALL  GMPRD(FREQ2,CONC,GLMULT,16,30,NUMDIS)
      GO TO 355
  350 CALL  GMPRD(FREQ3,CONC,GLMULT,16,30,NUMDIS)
  355 CALL  SMPY(GLMULT,SO2EMS,GLCONS,16,NUMDIS,0)
      CALL  SMPY(GLMULT,PEMS  ,GLCONP,10,NUMDIS,0)
C
C SEARCH FOR MAXIMUM VALUES OF SO2 AND PARTICULATE CONCENTRATIONS.
      TEMP=0.0
      DO 520 I=1,16
      DO 520 J=1,NUMDIS
      IF(GLMULT(I,J).LE.TEMP)   GO TO 520
  360 TEMP=GLMULT(I,J)
      IID=I
      JID=J
  520 CONTINUE
      SGLAN =TEMP*SO2EMS
      PGLAN =TEMP*PEMS
      DIST=X(JID)
      IF(IDGAST.EQ.1)  DIST=X(JID)/10.                               *GAS*
C
C TEST MAXIMUM OF SO2 AND PARTICULATES AGAINST THEIR STANDARD FOR ANNUAL
C AIR QUALITY.  IF PLANT PASSES, PRINT RESULTS AND PROCEED TO COST SECTION.
      IF(SGLAN .GT.(SGLA  (INDXST)-SBG(IDBGRD)))   GO TO 365
      IF(PGLAN .GT.(PGLA  (INDXST)-PBG(IDBGRD)))   GO TO 365
      APACOM(1)=1
      IF(CNTRL(3).EQ.1)  WRITE(6,900)
      IF(CNTRL(3).EQ.1)  WRITE(6,860)
      IF(CNTRL(3).EQ.1)  WRITE(6,825)   PERSO2,SEL(INDXST),PERP,PEL(INDX
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                   1ST)
 0263               IF(CNTRL(3).EQ.1)  WRITE(6,835)   SGL3,SGL3M(INDXST),PGL3,PGL3M(IN
                   1DXST)
 0264               IF(CNTRL(3).EQ.1)  WRITE(6,845)   SGL24,SGL24M(INDXST),PGL24,PGL24
                   1M(INDXST)
 0265               IF(CNTRL(3).EQ.1)  WRITE(6,855)   SGLAN,SGLA(INDXST),PGLAN,PGLA(IN
                   1DXST)
 0266               IF(CNTRL(3).EQ.1)  WRITE(6,836)   HEF3M,XMMD,STACK,SBG(IDBGRD),PBG
                   1(IDBGRD)
 0267               IF(CNTRL(3).EQ.1)  WRITE(6,856)   DIR(IID),DIST,QH
 0268               IF((CNTRL(3).EQ.1).AND.(IDSITE.EQ.2))   WRITE(6,837)  ALT
 0269               IF(IDGAST.EQ.1)  GO TO 150                                     *GAS*
 0270               GO TO 600
 0271           150 IF(CNTRL(3).EQ.1)  WRITE(6,900)                                  *GAS*
 0272               IF(CNTRL(3).EQ.1)  WRITE(6,151)                                  *GAS*
 0273               CSTAAB=0.                                                        *GAS*
 0274               FOCAA =0.                                                        *GAS*
 0275               VOCAA =0.                                                        *GAS*
 0276               RRA(2)=0.                                                        *GAS*
 0277               RRA(3)=0.                                                        *GAS*
 0278               POWRAA=0.                                                        *GAS*
 0279               DBEFF =0.                                                        *GAS*
 0280           151 FORMAT(1H ,'GAS TURBINE OR COMBINED CYCLE PLANTS USE NO ABATEMENT   *GAS*
                   1EQUIPMENT.  STACK COSTS ARE NEGLIGIBLE FOR THESE UNITS.'/1X,     *GAS*
                   2'THEREFORE, ECONOMIC AND RESOURCE COSTS ARE ALL ZERO.')         *GAS*
 0281               GO TO 1000                                                       *GAS*
              C
              C IF PLANT FAILS , AND THE STACK HEIGHT LOOP IS COMPLETED, PLANT SITE
              C ABATEMENT(PSA) COMBINATION IS INFEASIBLE, SO TERMINATE.  PRINT RESULTS.
              C OTHERWISE, INCREMENT STACK HEIGHT AND REPEAT CALCULATIONS.
 0282           365 IF(K.LT.NUMHT)   GO TO  515
 0283               APACOM(1)=0
 0284               CALL WHEN(TIME)                                                 *GENX*
 0285               IF(CNTRL(3).NE.1)  WRITE(15,706) (TIME(III),III=3,5),(PID(IIM),IIM  *GENX*
                   1=1,7)                                                           *GENX*
 0286               IF(CNTRL(3).EQ.1)  WRITE(6,850)
 0287               IF(CNTRL(3).EQ.1)  WRITE(6,900)
 0288               IF(CNTRL(3).EQ.1)  WRITE(6,825)   PERSO2,SEL(INDXST),PERP,PEL(INDX
                   1ST)
 0289               IF(CNTRL(3).EQ.1)  WRITE(6,835)   SGL3,SGL3M(INDXST),PGL3,PGL3M(IN
                   1DXST)
 0290               IF(CNTRL(3).EQ.1)  WRITE(6,845)   SGL24,SGL24M(INDXST),PGL24,PGL24
                   1M(INDXST)
 0291               IF(CNTRL(3).EQ.1)  WRITE(6,855)   SGLAN,SGLA(INDXST),PGLAN,PGLA(IN
                   1DXST)
 0292               IF(CNTRL(3).EQ.1)  WRITE(6,836)   HEF3M,XMMD,STACK,SBG(IDBGRD),PBG
                   1(IDBGRD)
 0293               IF(CNTRL(3).EQ.1)  WRITE(6,856)   DIR(IID),DIST,QH
 0294               IF((CNTRL(3).EQ.1).AND.(IDSITE.EQ.2))   WRITE(6,837)  ALT
 0295               GO TO 1000
 0296           515 CONTINUE
              C
              C BRANCH TO APPROPRIATE ABATEMENT METHOD.
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      600 GO TO (601,602,603,604), IDAPAM
      601 CONTINUE
C
C WET LIMESTONE
          GASFLO=1.E+6*SGCF(4)*(FTOC(SGTEMP)+273.)/(FTOC(SGCF(5))+273.)
          IF(CNTRL(3).EQ.1)  WRITE(6,901)
          GO TO 605
C
C CATALYTIC OXIDATION
      602 CONTINUE
          READ(18'RN, 6)      COTEMP,CATLST,CATATT,H2OEVP,H2OCOL,PWRPRC           CO  5
          READ(18'RN, 4)      DPTOTL,CATALC,WATERC,COOLWC                         CO  6
          GASFLO=1.E+6*SGCF(4)*(FTOC(SGTEMP)+273.)/(FTOC(SGCF(5))+273.)
          IF(CNTRL(3).EQ.1)  WRITE(6,902)
          GO TO 605
C
C MAGNESIUM SCRUBBING
      603 CONTINUE
          READ(18'RN, 6)      H2OEVP,ACIDOS,ACIDCS,MGOXIC,DPTOTL,ACIDOC           MG  7
          READ(18'RN, 2)      ACIDCC,WATERC                                       MG  8
          GASFLO=1.E+6*SGCF(4)*(FTOC(SGTEMP)+273.)/(FTOC(SGCF(5))+273.)
          IF(CNTRL(3).EQ.1)  WRITE(6,903)
          GO TO 605
C
C TALL STACKS
      604 CONTINUE
          READ(18'RN, 2)      PWRPRC,DPTOTL                                       TS  5
          GASFLO=1.E+6*SGCF(4)*(FTOC(SGTEMP)+273.)/(FTOC(SGCF(5))+273.)
          IF(CNTRL(3).EQ.1)  WRITE(6,904)
C
C CALCULATE COSTS COMMON TO ALL ABATEMENT METHODS, ESPECIALLY CAPITAL
C COSTS AND ELECTRIC POWER CONSUMPTION. FOR THE APPROPRIATE METHODS,
C INCLUDE EXTRA POWER AND CAPITAL COSTS
      605 LABCST=LABOR*LABORC*8760.
          SUPCST=PCTSUP*LABCST/100.
          TRSIZE=1.E+6*TRSIZE
          TRAIN =AINT(GASFLO/TRSIZE + 0.90)
          APACST=TRAINC*PLSIZE*1000.
          IF(IDAPAM.EQ.3)  APACST=APACST+ACIDCC*ACIDCS*10000.
          STKCST=(STCSTA*STACK *STACK +STCSTB*STACK +STCSTC)*1000.
          CSTAAB=APACST+STKCST
          MATCST=PCTMAT*CSTAAB/100.
          PLTCST=PCTSPY*MATCST/100.
          PAYCST=PCTPAY*(LABCST+SUPCST)/100.
          POHCST=PCTPLT*(LABCST+SUPCST+MATCST+PLTCST)/100.
          PMPPWR=PMPREQ*TRAIN *0.74604
          ASHHR =FLYASH*PEFF/200000.
          AREASH=ASHHR*STREAM*DISPAA/100.
          POWRAA=1.955E-4*DPTOTL*GASFLO
          IF(IDAPAM.EQ.3)  POWRAA=POWRAA+DRYPWR
          IF((IDAPAM.EQ.2).OR.(IDAPAM.EQ.4))   POWRAA=POWRAA+PWRPRC*TRAIN
          ELECHR=POWRAA*STREAM
          ELECST=POWRAA*STREAM*ELECTC*1.E-3
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0338                CAPCST=CAPCHG*CSTAAB/100.
0339                FOCAA =LABCST+SUPCST+MATCST+PLTCST+PAYCST+POHCST
0340                IF(APACOM(3).EQ.1)  FOCAA =FOCAA +CAPCST
              C
              C OUTPUT ABATEMENT DESCRIPTION, CAPITAL COSTS, FIXED OPERATING
              C COSTS AND OPERATING PARAMETERS.
0341                IF(CNTRL(3).EQ.1)   WRITE(6,900)
0342                IF(CNTRL(3).EQ.1)  WRITE(6,905)   PID(3),STKCST,TRSIZE,APACST,GASF
                   1LO,CSTAAB,TRAIN,STREAM
0343                IF(CNTRL(3).EQ.1)  WRITE(6,900)
0344                IF(CNTRL(3).EQ.1)  WRITE(6,910)   LABOR,LABORC,LABCST,SO2EFF,PCTSU
                   1P,SUPCST,PEFF
0345                IF(CNTRL(3).EQ.1)  WRITE(6,915)   PCTMAT,MATCST,POWRAA,PCTSPY,PLTC
                   1ST,AREASH,PCTPAY,PAYCST,DPTOTL
0346                IF((CNTRL(3).EQ.1).AND.(APACOM(3).NE.1))  WRITE(6,920)   PCTPLT,PO
                   1HCST,SGTEMP,FOCAA,PMPPWR
0347                IF((CNTRL(3).EQ.1).AND.(APACOM(3).EQ.1)) WRITE(6,921)   PCTPLT,POH
                   1CST,SGTEMP,CAPCHG,CAPCST,PMPPWR,FOCAA
0348                IF(CNTRL(3).EQ.1)  WRITE(6,900)
0349                POWRAA=POWRAA*1.E-3
0350                GO TO (1100,1200,1300,1400),  IDAPAM
              C
              C CALCULATE RESOURCE REQUIREMENTS, BOILER EFFICIENCY CHANGE AND
              C PERFORMANCE DATA FOR THE DIFFERENT ABATEMENT METHODS.  OUTPUT COSTS.
              C WET LIMESTONE
0351           1100 CAOHOH=74.*56.*100.*AVFUEL*SO2EF *PCTSUL*STOICH*(100.-BOILER)*(100
                   1.-SO2EFF)/(56.*100.*100.*100.*64.*100.*2000.)
0352                LIMPHR=LIMEP *PEFF /200000.+128.*AVFUEL*SO2EF *PCTSUL*(SO2EFF-BOIL
                   1ER)/(64.*100.*2000.) +CAOHOH
0353                AREAL =DISPAL*LIMPHR*STREAM/100.
0354                RRA(3)=AREASH+AREAL
0355                H2OCAO=18.*2000.*CAOHOH/74.
0356                RRA(2)=(H2OSCB*TRAIN +H2OEVP*RRA(3)+H2OCAO)/(8.3*3600.)
0357                DBEFF =-CALCHL*LIMEHR*1.E+8/SGCF(6)
0358                RRA(4)=APL(INDXST)
0359                H2OCST=RRA(2)*3600.*STREAM*WATERC/1.E+6
0360                LIMCST=LIMEHR*STREAM*LIMESC
0361                DSLCST=LIMPHR*STREAM*DISPLC
0362                DSACST=ASHHR *STREAM*DISPAC
0363                CRED  =CREDAA*PLSIZE*STREAM*BYPROD*1000.
0364                VOCCST=H2OCST+LIMCST+DSLCST+DSACST-CRED
0365                IF(APACOM(3).EQ.1)  VOCCST=VOCCST+ELECST
0366                VOCAA =VOCCST/100.
0367                IF(CNTRL(3).EQ.1)  WRITE(6,900)
0368                IF(CNTRL(3).EQ.1)  WRITE(6,925)   CACO3,CALCHL,RRA(3),WATERC,H2OCS
                   1T,STOICH
0369                IF(CNTRL(3).EQ.1)  WRITE(6,930)   LIMEHR,LIMESC,LIMCST,AREAL, ASHH
                   1R,DISPAC,DSACST,DBEFF
0370                IF(CNTRL(3).EQ.1)  WRITE(6,935)   LIMPHR,DISPLC,DSLCST,CAOHOH,CRED
0371                IF((CNTRL(3).EQ.1).AND.(APACOM(3).NE.1)) WRITE(6,940) VOCCST,VOCAA
0372                IF((CNTRL(3).EQ.1).AND.(APACOM(3).EQ.1)) WRITE(6,941)   ELECHR,ELE
                   1CTC,ELECST,VOCCST,VOCAA
0373                GO TO 2000
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                  C
                  C CATALYTIC OXIDATION
 0374              1200 RRA(3)=AREASH
 0375                   RRA(2)=(SO2REM*(18./64.+0.223*98./(64.*0.777))+H2OEVP)/(8.3*3600.)
 0376                   RRA(4)=APL(INDXST)
 0377                   DBEFF =0.
 0378                   ACID77=SO2REM*98./(64.*0.777*2000.)
 0379                   CATLOD=CATLST*TRAIN
 0380                   CAMKUP=CATLOD*CATATT/100.
 0381                   CATCST=CAMKUP*CATALC
 0382                   DSACST=ASHHR *STREAM*DISPAC
 0383                   H2OCST=RRA(2)*3600.*STREAM*WATERC/1.E+6
 0384                   COLCST=H2OCOL*3600.*STREAM*COOLWC/1.E+6
 0385                   CRED  =CREDAA*ACID77*STREAM *BYPROD
 0386                   VOCCST=H2OCST+CATCST+DSACST-CRED
 0387                   IF(APACOM(3).EQ.1)  VOCCST=VOCCST+ELECST
 0388                   VOCAA =VOCCST/100.
 0389                   IF(CNTRL(3).EQ.1)  WRITE(6,900)
 0390                   IF(CNTRL(3).EQ.1)  WRITE(6,965)   COTEMP,CATLOD,RRA(2),WATERC,H2OC
                       1ST,CATATT
 0391                   IF(CNTRL(3).EQ.1)  WRITE(6,970)   CAMKUP,CATALC,CATCST,DBEFF,ASHHR
                       1 ,DISPAC,DSACST,H2OCCL,COOLWC,COLCST
 0392                   IF((CNTRL(3).EQ.1).AND.(APACOM(3).NE.1))  WRITE(6,975)    ACID77,C
                       1REDAA,CRED  ,VOCCST,VOCAA
 0393                   IF((CNTRL(3).EQ.1).AND.(APACOM(3).EQ.1)) WRITE(6,976)   ACID77,CRE
                       1DAA,CRED  ,ELECHR,ELECTC,ELECST,VOCCST,VOCAA
 0394                   GO TO 2000
                  C
                  C MAGNESIUM SCRUBBING
 0395              1300 RRA(3)=AREASH+DRYASH*DRYCAK*STREAM*DISPAA*DRYEFF/2.E+7
 0396                   RRA(2)=(SO2REM*(PCT3HY*3.+PCTSO4*7.+(100.-PCT3HY-PCTSO4)*6.)*18./6
                       1400.+CRSWET*2000.*WETCAK/100.+H2OSCB*TRAIN+H2OEVP*AREASH)/(8.3*360
                       20.)
 0397                   CRSDRY=(100.-WETCAK)*CRSWET/100.
 0398                   DBEFF =0.
 0399                   RRA(4)=APL(INDXST)
 0400                   H2OCST=RRA(2)*3600.*STREAM*WATERC/1.E+6
 0401                   DSACST=ASHHR *STREAM*DISPAC
 0402                   CRED  =CREDAA*DRYCAK*STREAM*BYPROD
 0403                   MGMKUP=SPYMGO*MAKEUP*SO2REM*TRAIN/200000.
 0404                   MGOCST=MGMKUP*MGOXIC*STREAM
 0405                   DRYBTU=DRYFUL*CRSWET
 0406                   DRYCST=DRYBTU*DRYFUC*STREAM
 0407                   ACOCST=ACIDOS*ACIDOC*DRYCAK*STREAM/100.
 0408                   VOCCST=H2OCST+MGOCST+DRYCST+DSACST+ACOCST-CRED
 0409                   IF(APACOM(3).EQ.1)  VOCCST=VOCCST+ELECST
 0410                   VOCAA =VOCCST/100.
 0411                   IF(CNTRL(3).EQ.1)  WRITE(6,900)
 0412                   IF(CNTRL(3).EQ.1)  WRITE(6,945)   ACIDCC,ACIDCS,RRA(2),WATERC,H2OC
                       1ST,DBEFF
 0413                   IF(CNTRL(3).EQ.1)  WRITE(6,950)   MGMKUP,MGOXIC,MGOCST,DRYPWR,DRYB
                       1TU,DRYFUC,DRYCST,DRYEFF
 0414                   IF((CNTRL(3).EQ.1).AND.(APACOM(3).NE.1)) WRITE(6,955)   ASHHR ,DIS
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                        1PAC,DSACST,DRYPCT,DRYCAK,ACIDOC,ACIDOS,ACOCST,SPYMGO
0415                     IF(APACOM(3).EQ.1) WRITE(6,956)   ASHHR ,DISPAC,DSACST,DRYPCT,DRYC
                        1AK,ACIDOC,ACIDOS,ACOCST,SPYMGO,ELECHR,ELECTC,ELECST
0416                     IF((CNTRL(3).EQ.1).AND.(APACOM(3).NE.1))   WRITE(6,960)   DRYCAK,C
                        1REDAA,CRED  ,PCTSO4,VOCCST,PCT3HY,VOCAA
0417                    ·IF((CNTRL(3).EQ.1).AND.(APACOM(3).EQ.1)) WRITE(6,961)   DRYCAK,CRE
                        1DAA,CRED  ,PCTSO4,VOCCST,PCT3HY,VOCAA
0418                     GO TO 2000
                  C
                  C TALL STACKS
0419               1400 RRA(3)=AREASH
0420                     RRA(2)=0.
0421                     RRA(4)=APL(INDXST)
0422                     DREFF =0.
0423                     DSACST=ASHHR *STREAM*DISPAC
0424                     CRED  =CREDAA*PLSIZE*STREAM*BYPROD*1000.
0425                     VOCCST=DSACST-CRED
0426                     IF(APACOM(3).EQ.1)  VOCCST=VOCCST+ELECST
0427                     VOCAA =VOCCST/100.
0428                     IF(CNTRL(3).EQ.1)  WRITE(6,900)
0429                     IF((CNTRL(3).EQ.1).AND.(APACOM(3).NE.1))   WRITE(6,980)   PWRPRC,D
                        1REFF,CRED,ASHHR,DISPAC,DSACST,VOCCST,VOCAA
0430                     IF((CNTRL(3).EQ.1).AND.(APACOM(3).EQ.1)) WRITE(6,981)   PWRPRC,DRE
                        1FF ,CRED  ,ASHHR ,DISPAC,DSACST,ELECHR,ELECTC,ELECST,VOCCST,VOCAA
0431               2000 IF(CNTRL(3).EQ.1)  WRITE(6,900)
0432                     TRSIZE=TRSIZE*1.E-6
0433                     IF(CNTRL(3).NE.1)  GO TO 1000
                  C
                  C ABATEMENT PARAMETER OUTPUT
0434                     GO TO(1510,1520,1530,1540), IDAPAM
0435               1510 WRITE(6,6)          SO2EFF,PEFF  ,SGTEMP,STREAM,TRSIZE,DISPAA        COM 1
0436                     WRITE(6,6)          LABOR ,PMPREQ,TRAINC,DISPAC,CREDAA,PCTMAT        COM 2
0437                     WRITE(6,6)          STCSTA,STCSTB,STCSTC,CAPCHG,LABORC,PCTSUP        COM 3
0438                     WRITE(6,4)          PCTSPY,PCTPAY,PCTPLT,ELECTC                      COM 4
0439                     WRITE(6,6)          CACO3 ,STOICH,CALCHL,DISPAL,H2OEVP,H2OSCB        WL  5
0440                     WRITE(6,5)          DPTOTL,LIMESC,DISPLC,WATERC,BOILER               WL  6
0441                     GO TO 1000
0442               1520 WRITE(6,6)          SO2EFF,PEFF  ,SGTEMP,STREAM,TRSIZE,DISPAA        COM 1
0443                     WRITE(6,6)          LABOR,PMPREQ,TRAINC,DISPAC,CREDAA,PCTMAT         COM 2
0444                     WRITE(6,6)          STCSTA,STCSTB,STCSTC,CAPCHG,LABORC,PCTSUP        COM 3
0445                     WRITE(6,4)          PCTSPY,PCTPAY,PCTPLT,ELECTC                      COM 4
0446                     WRITE(6,6)          COTEMP,CATLST,CATATT,H2OEVP,H2OCOL,PWRPRC        CO  5
0447                     WRITE(6,4)          DPTOTL,CATALC,WATERC,COOLWC
0448                     GO TO 1000
0449               1530 WRITE(6,6)          SO2EFF,PEFF  ,SGTEMP,STREAM,TRSIZE,DISPAA        COM 1
0450                     WRITE(6,6)          LABOR ,PMPREQ,TRAINC,DISPAC,CREDAA,PCTMAT        COM 2
0451                     WRITE(6,6)          STCSTA,STCSTB,STCSTC,CAPCHG,LABORC,PCTSUP        COM 3
0452                     WRITE(6,4)          PCTSPY,PCTPAY,PCTPLT,ELECTC                      COM 4
0453                     WRITE(6,6)          WETCAK,PCT3HY,PCTSO4,SPYMGO,MAKEUP,H2OSCB        MG  5
0454                     WRITE(6,6)          DRYFUL,DRYPCT,DRYFUC,DRYASH,DRYEFF,DRYPWR        MG  6
0455                     WRITE(6,6)          H2OEVP,ACIDOS,ACIDCS,MGOXIC,DPTOTL,ACIDOC        MG  7
0456                     WRITE(6,2)          ACIDCC,WATERC                                    MG  8
0457                     GO TO 1000
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 0458            1540 WRITE(6,6)         SO2EFF,PEFF   ,SGTEMP,STREAM,TRSIZE,DISPAA         COM 1
 0459                 WRITE(6,6)         LABOR,PMPREQ,TRAINC,DISPAC,CREDAA,PCTMAT           COM 2
 0460                 WRITE(6,6)         STCSTA,STCSTB,STCSTC,CAPCHG,LABORC,PCTSUP          COM 3
 0461                 WRITE(6,4)         PCTSPY,PCTPAY,PCTPLT,ELECTC                        COM 4
 0462                 WRITE(6,2)         PWRPRC,DPTOTL                                      TS  5
 0463               2 FORMAT(2F12.5,56X)
 0464               4 FORMAT(4F12.5,32X)
 0465               5 FORMAT(5F12.5,20X)
 0466               6 FORMAT(6F12.5, 8X)
 0467             701 FORMAT(1H0,3A4,T16,'MA1  PLANT TYPE ',A4,' USES GAS TURBINES. ABAT  *GENX*
                     1EMENT ECONOMICS ARE NEGLIGIBLE, AND ALL ARE SET TO ZERO.')         *GENX*
 0468             702 FORMAT(1H0,3A4,T16,'MA2  FOR SITE TYPE ',A4,' METEOROLOGICAL DATA   *GENX*
                     1IS LISTED.')                                                       *GENX*
 0469             703 FORMAT(1H0,3A4,T16,'MA3  PLANT TYPE ',7(A4,1X),' FAILS EMISSIONS T  *GENX*
                     1EST.')                                                             *GENX*
 0470             704 FORMAT(1H0,3A4,T16,'MA4  PLANT TYPE ',7(A4,1X),' FAILS 3HR AQ TEST  *GENX*
                     1.')                                                                *GENX*
 0471             705 FORMAT(1H0,3A4,T16,'MA5  PLANT TYPE ',7(A4,1X),' FAILS 24HR AQ TES  *GENX*
                     1T.')                                                               *GENX*
 0472             706 FORMAT(1H0,3A4,T16,'MA5  PLANT TYPE ',7(A4,1X),' FAILS ANNUAL AQ T  *GENX*
                     1EST.')                                                             *GENX*
 0473             751 FORMAT(1H0,3A4,T16,'EA1  PLANT TYPE ',A4,' CANNOT BE EVALUATED BY   *GENX*
                     1APA. RETURN.')                                                     *GENX*
 0474             752 FORMAT(1H0,3A4,T16,'EA2  FUEL TYPE ',A4,' CANNOT BE USED IN A GAS   *GENX*
                     1TURBINE IF APA IS TO EVALUATE AIR POLLUTION EFFECTS. RETURN.')     *GENX*
 0475             753 FORMAT(1H0,3A4,T16,'EA2  FUEL TYPE ',A4,' CANNOT BE USED IN A GAS   *GENX*
                     1TURBINE IF APA IS TO EVALUATE AIR POLLUTION EFFECTS. RETURN.')     *GENX*
 0476             754 FORMAT(1H0,3A4,T16,'EA4  FOR FUEL TYPE ',A4,' PLANT TYPE ',A4,' DO  *GENX*
                     1ES NOT SPECIFY COMBUSTION METHOD. RETURN.')                        *GENX*
 0477             815 FORMAT(1H1,45X,'AIR POLLUTION COST CONTROL PROGRAM'/2X,'PLANT ID C
                     1ODE',5X,2(A4,3X),2(I5,2X),3(A4,3X)//2X,'PLANT TYPE    = ',A4,'  SI
                     2TE TYPE    = ',A4,'  FUEL TYPE      = ',A4,'  SO2 EMISSION FACTOR
                     3= ',F6.1,'  SO2EMB = ',F8.0,' G/S,'/2X,'PLANT SIZE    =',I5,'  URB
                     4ANIZATION = ',A4,'  SULFUR CONTENT = ',F4.1,'  PARTICULATE E.F.
                     5 = ',F6.1,'  PEMB   = ',F8.0,' G/S'/2X,'PLANT VINTAGE =',I5,'  ABA
                     6TEMENT    = ',A4,'  ASH CONTENT    = ',F4.1,'  BYPRODUCT CREDITS
                     7 = ',F6.1,'  AVFUEL = ',F8.0,' UPH')
 0478             820 FORMAT(1H0,   'SYSTEM FAILS TO MEET STACK EMISSION STANDARDS')
 0479             825 FORMAT(1H ,1X,'      SO2           ',10X,'   SO2  ',21X,'   PARTICUL
                     1ATES   ',10X,' PARTICULATES '/2X,'STACK EMISSIONS   = ',F7.2,' STA
                     2NDARD= ',F7.2,' G/MCAL',5X,'STACK EMISSIONS   = ',F7.2,' STANDARD=
                     3 ',F7.2,'G/MCAL')
 0480             830 FORMAT(1H0,   'SYSTEM FAILS TO MEET 3 HR GROUND LEVEL STANDARDS,BU
                     1T IT DOES MEET EMISSION STANDARDS')
 0481             835 FORMAT(1H ,1X,'3 HR GL MAX CONC  = ',F7.2,' STANDARD= ',F7.2,' MMG
                     1/CU.M   3 HR GL MAX CONC  = ',F7.2,' STANDARD= ',F7.2,' MMG/CU.M')
 0482             836 FORMAT(1H ,1X,'LIMITED MIXING DEPTH= ',F5.0,' M, AT ',F7.0,' M; ST
                     1ACK HT= ',F4.0,'M; SO2 BGRND= ',F7.3,'MMG/CU.M PART BGRND= ',F7.3,
                     2'MMG/CU.M')
 0483             837 FORMAT(1H ,' VALLEY DEPTH IS',F8.0,'M')
 0484             840 FORMAT(1H0,   'SYSTEM FAILS TO MEET 24HR GROUND LEVEL STANDARDS,BU
                     1T IT DOES MEET EMISSION STANDARDS AND 3HR GROUND LEVEL STANDARDS')
 0485             845 FORMAT(1H ,1X,'24HR GL MAX CONC  = ',F7.2,' STANDARD= ',F7.2,' MMG
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                 1/CU.M   24HR GL MAX CONC  = ',F7.2,' STANDARD= ',F7.2,' MMG/CU.M')
0486          850 FORMAT(1HO,   'SYSTEM FAILS TO MEET ANNUAL GROUND LEVEL STANDARDS,
                 1BUT IT MEETS THE 3HR,24HR AND STACK EMISSION STANDARDS')
0487          855 FORMAT(1H ,1X,'ANNUAL GL MAX CONC= ',F7.2,' STANDARD= ',F7.2,' MMG
                 1/CU.M   ANNUAL GL MAX CONC= ',F7.2,' STANDARD= ',F7.2,' MMG/CU.M')
0488          856 FORMAT(1H ,1X,'ANNUAL MAX GL CONC IN ',A3,' DIRECTION AT ',F7.0,'M
                 1ETERS DOWNWIND',5X,'STACK HEAT EMISSION  = ',F12.0,' BTU/HR')
0489          860 FORMAT(1HO,   'SYSTEM MEETS ALL AIR POLLUTION STANDARDS')
0490          900 FORMAT(24('.....'))
0491          901 FORMAT(1HO,47X,'WET LIMESTONE SCRUBBING')
0492          902 FORMAT(1HO,49X,'CATALYTIC OXIDATION')
0493          903 FORMAT(1HO,46X,'MAGNESIUM OXIDE SCRUBBING')
0494          904 FORMAT(1HO,45X,'TALL STACK WITH PRECIPITATOR')
0495          905 FORMAT(1H ,47X,'ANNUAL OPERATING DATA'/6X,'PLANT SIZE (MW)',13X,I5
                 1,44X,    'STACK CAPITAL COSTS      $',F10.0/6X,'TRAIN SIZE (ACFM)',
                 26X,F10.0,41X,     'EQUIPMENT CAPITAL COST     $',F10.0/6X,'GAS FLO
                 3W (ACFM)',8X,F10.0,34X,   'FIXED CAPITAL INVESTMENT(FCI)      $',F1
                 40.0/6X,'NUMBER OF TRAINS',7X,F10.0,44X,    'STREAM TIME (HR/YR)
                 5   ',F10.0)
0496          910 FURMAT(1HO,'FIXED OPERATING COSTS',51X,'....$/YR..',5X,'SYSTEM DAT
                 1A'/              /3X,'1. OPERATING LABOR (',F3.0,' MEN/SHIFT @ $ ',F
                 25.2,'/HR)',22X,     F10.0,' XX SO2 REMOVAL EFF        ',F7.1,' %'/
                 33X,'2. SUPERVISION ',F5.1,'% OF ITEM 1',38X,    F10.0,' XX PART RE
                 4MOVAL EFF       ',F7.1,' %')
0497          915 FORMAT(1H ,2X,'3. MAINTENANCE LABOR AND MATERIALS ',F5.1,'% OF FCI
                 1',21X,    F10.0,' XX TOTAL ELCTRIC PCWER  ',F7.1,' KW'/3X,'4. PLAN
                 2T SUPPLIFS ',F5.1,'% OF ITEM 3',35X,   F10.0,' XX FLYASH DISP AREA
                 3       ',F7.1,' A'/3X,'5. PAYROLL OVERHEAD ',F5.1,'% OF (1+2)',34X,
                 4  F10.0,' XX PRESSURE DROP          ',F7.1,' IN')
0498          920 FORMAT(1H ,2X,'6. PLANT OVERHEAD ',F5.1,'% OF (1+2+3+4)',32X,
                 1F10.0,' XX STACK GAS TEMP        ',F7.1, ' F'/3X,'7. TOTAL FIXED OP
                 2ERATING COST..................................... $',F10.0,' XX P
                 3UMP ELEC POWER',6X,F7.1,' KW'/82X,' XX'/82X,' XX')
0499          921 FORMAT(1H ,2X,'6. PLANT OVERHEAD ',F5.1,'% OF (1+2+3+4)',32X,
                 1F10.0,' XX STACK GAS TEMP        ',F7.1, ' F'/3X,'7. CAPITAL CHARGE
                 2S  ',F5.1,'% OF FCI',36X,F10.0,' XX PUMP ELEC POWER',6X,F7.1,' KW'
                 3/3X,'8. TOTAL FIXED OPERATING COST................................
                 4...... $',F10.0,' XX'/82X,' XX')
0500          924 FORMAT(1H1,30X,'STABILITY WIND ROSE DATA        STABILITY CLASS ',
                 1A4//15X,'CLASS   WIND SPEED .....1.........2.........3.........4..
                 2.......5.........6.....'/)
0501          925 FORMAT(1HO,'VARIABLE OPERATING COSTS',58X,'XX CACO3 IN LIMESTONE
                 1 ',F7.1,' %'/83X,  'XX CALC HEAT/T LIMESTONE',F7.1,' BTU'/3X,'1. W
                 2ATER CONSUMPTION             ',F8.1,' GPS @$',F6.2,'/MGAL',13X,F10.0,
                 3' XX STOICHIOMETRIC RATE  ',F7.1,' %')
0502          930 FORMAT(1H ,2X,'2. LIMESTONE',18X,F8.1,' TPH @$',F6.2,'/TON',14X,F1
                 10.0,' XX SOLIDS DISP APEA       ',F7.1,' A'/2X,' 3. DISPOSAL OF FLYA
                 2SH',9X,F8.1,' TPH @$',F6.2,'/TON',14X,   F10.0,' XX BOILER EFF. CH
                 3ANGE    ',F7.1,' %')
0503          935 FORMAT(1H ,1X,' 4. DISPOSAL OF PROCESS SOLIDS ',F8.1,' TPH @$',F6.
                 12,'/TON',14X,  F10.0,' XX CAOHOH PRODUCTION     ',F7.1,' TPH'/2X,'
                 25. CREDITS',58X,'(',F10.0,')XX')
0504          940 FORMAT(1H ,1X,' 6. TOTAL VARIABLE OPERATING COSTS.................
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                          1................. $',F10.0,' XX'/3X,'7. CAPACITY FACTOR ADJUSTED V
                          2ARIABLE OPERATING COSTS',17X,F10.0,' XX')
 05C5                 941 FORMAT(1H ,1X,' 6. ELECTRICITY COST  ',F12.0,' KWH      @ '   ,F6.
                          12,'MILLS/KWH',9X,F10.0,' XX'/2X,' 7. TOTAL VARIABLE OPERATING COST
                          2S................................... $',F10.0,' XX'/2X,' 8. CAPACIT
                          3Y FACTOR ADJUSTED VARIABLE OPERATING COSTS',17X,F10.0,' XX')
 0506                 945 FORMAT(1H0,'VARIABLE OPERATING COSTS',58X,'XX ACID PLANT FCI      '
                          1,F7.1,' M$'/83X,'XX PLANT SHARE OF FCI ',F7.1,' %'/3X,'1. WATER CO
                          2NSUMPTION '   ,F8.1,' GPS             @ $',F6.2,'/MGAL',13X,F10.0,' XX
                          3 BOILER EFF CHANGE  ',F7.1,' %')
 0507                 950 FORMAT(1H ,2X,'2. MGC MAKEUP          ',F8.1,' TPH           @ $',F6.2
                          1,'/TON',14X,F10.0,' XX DRYER ELEC POWER   ',F7.1,' MW'/2X,' 3. DRY
                          2ER FUEL          ',F8.1,' MBTU/HR      @ $',F6.2,'/MBTU',13X,F10.0,'
                          3XX DRYER ASH COLL EFF ',F7.1,' %')
 0508                 955 FORMAT(1H ,1X,' 4. FLYASH DISPOSAL    ',F8.1,' TPH            @ $',F6.
                          12,'/TON',14X,F10.0,' XX DRYER STACK HEAT    ',F7.1,' %'   /2X,' 5.
                          2ACID PLANT COSTS  ',F8.1,' TPH DRYCAKF @ $',F6.2,'/TON' ,F6.1,'% S
                          3HARE ',F10.0,' XX INITIAL MGO LOADING' ,F7.1,' TON')
 0509                 956 FORMAT(1H ,1X,' 4. FLYASH DISPOSAL    ',F8.1,' TPH            @ $',F6.
                          12,'/TON',14X,F10.0,' XX DRYER STACK HEAT    ',F7.1,' %'   /2X,' 5.
                          2ACID PLANT COSTS  ',F8.1,' TPH DRYCAKE @ $',F6.2,'/TON ',F6.1,'% S
                          3HARE' ,F10.0,' XX INITIAL MGO LOADING' ,F7.1,' TON'/2X,' 6. ELECTR
                          4ICITY COST  ',F12.0,' KWH      @ '   ,F6.2,'MILLS/KWH',9X,F10.0,'
                          5XX')
 0510                 960 FORMAT(1H ,1X,' 6. CREDITS             ',F8.1,' TPH DRYCAKE @ $',F6.
                          12,'/TON',13X,'(',F10.0,')XX SO2 TO MGSO4',7X,F7.1,' %'/2X,' 7. TOT
                          2AL VARIABLE OPERATING COSTS................................. $',F
                          310.0,' XX SO2 TO MGSO3.3H2O  ',F7.1,' %'/2X,' 8. CAPACITY FACTOR A
                          4DJUSTED VARIABLE OPERATING COSTS',17X,F10.0,' XX')
 0511                 961 FORMAT(1H ,1X,' 7. CREDITS             ',F8.1,' TPH DRYCAKE @ $',F6.
                          12,'/TON',13X,'(',F10.0,')XX SO2 TO MGSO4',7X,F7.1,' %'/2X,' 8. TOT
                          2AL VARIABLE OPERATING COSTS................................. $',F
                          310.0,' XX SO2 TO MGSO3.3H2O  ',F7.1,' %'/2X,' 9. CAPACITY FACTOR A
                          4DJUSTED VARIABLE OPERATING COSTS',17X,F10.0,' XX')
 0512                 965 FORMAT(1H0,'VARIABLE OPERATING COSTS',58X,'XX CATALYST GAS TEMP  '
                          1,F7.1,' F'/83X,'XX CATALYST LOADING   ',F7.1,' CU.FT'/3X,'1. WATER
                          2 CONSUMPTION ',F8.1,' GPS',8X, ' @ $',F6.2,'/MGAL',13X,F10.0,' XX
                          3CATALYST ATTRITION ',F7.1,' %')
 0513                 970 FORMAT(1H ,2X,'2. CATALYST MAKEUP   ',F8.1,' CU.FT.      @ $',F6.2
                          1,'/CU.FT.',11X,F10.0,' XX BOILER EFF CHANGE  ',F7.1,' %'/2X,' 3. F
                          2LYASH DISPOSAL    ',F8.1,' TPH          @ $',F6.2,'/TON',14X,F10.0,'
                          3 XX'/2X,' 4. COOLING WATER      ',F8.1,' LB/HR        @ $',F6.2,'/MG
                          4AL              ',F10.0,' XX')
 0514                 975 FORMAT(1H ,1X,' 5. CREDITS             ' ,F8.1,' TPH H2SO4   @ $',F6
                          1.2,'/TON 77.7% ACID  (',F10-0,')XX'/2X,' 6. TOTAL VARIABLE OPERATI
                          2NG COSTS................................... $' ,F10.0,' XX'/2X,' 7.
                          3 CAPACITY FACTOR ADJUSTED VARIABLE OPERATING COSTS',17X,F10.0,' XX
                          4')
 0515                 976 FORMAT(1H ,1X,' 5. CREDITS             ' ,F8.1,' TPH H2SO4   @ $',F6
                          1.2,'/TON 77.7% ACID  (',F10.0,')XX'/2X,' 6. ELECTRICITY COST  ',F1
                          22.0,' KWH     @ '   ,F6.2,'MILLS/KWH',10X,F10.0,' XX'/2X,
                          3' 7. TOTAL VARIABLE OPERATING COSTS..................................
                          4... $' ,F10.0,' XX'/2X,' 8. CAPACITY FACTOR ADJUSTED VARIABLE OPER
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                    5ATING COSTS',17X,F10.0,' XX')
 0516           980 FORMAT(1H0,'VARIABLE OPERATING COSTS',58X,'XX PRECIPITATOR POWER '
                    1,F7.1,' MW'/83X,'XX BOILER EFF CHANGE  ',F7.1,' %'/3X,'1. CREDITS'
                    2,58X,'(',F10.0,')XX'/2X,' 2. FLYASH DISPOSAL   ',F8.1,' TPH
                    3  @ $',F6.2,'/TON',14X,F10.0,' XX'/2X,' 3. TOTAL VARIABLE OPERATIN
                    4G COSTS.............................. $',F10.0,' XX'/3X,'4. CA
                    5PACITY FACTOR ADJUSTED VARIABLE OPERATING COSTS',17X,F10.0,' XX')
 0517           981 FORMAT(1H0,'VARIABLE OPERATING COSTS',58X,'XX PRECIPITATOR POWER
                    1 ',F7.1,' KW'/83X,'XX BOILER EFF CHANGE    ',F7.1,' %'/3X,'1. CRED
                    2ITS',58X,'(',F10.0,')XX'/2X,' 2. FLYASH DISPOSAL   ',F8.1,' TPH
                    3      @ $',F6.2,'/TON',14X,F10.0,' XX'/2X,' 3. ELECTRICITY COST  '
                    4,F12.0,' KWH',5X,'@  ',F6.2,'MILLS/KWH',9X,F10.0,' XX'/2X,' 4. TOT
                    5AL VARIABLE OPERATING COSTS................................ $',F
                    610.0,' XX'/2X,' 5. CAPACITY FACTOR ADJUSTED VARIABLE OPERATING COS
                    7TS',17X,F10.0,' XX')
 0518           995 FORMAT(15X,A3,8X,A3,5X,6F10.5//)
 0519          1000 RETURN
 0520                END
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