Department of Engineering and Public Policy | Carnegie Institute of Technology

11-1-1991

A Probabilistic Emissions Model for Managing Hazardous Air Pollutants

Edward S. Rubin
Carnegie Mellon University, rubin@cmu.edu

Michael B. Berkenpas
Carnegie Mellon University

Follow this and additional works at: http://repository.cmu.edu/epp

Part of the Engineering Commons

A PROBABILISTIC EMISSIONS MODEL FOR MANAGING HAZARDOUS AIR POLLUTANTS

Edward S. Rubin and Michael B. Berkenpas
Carnegie Mellon University
Pittsburgh, PA 15213

for presentation at

I.   ABSTRACT

Any assessment of control strategies or impacts of potentially hazardous airborne pollutants must begin with the characterization of source emissions. This paper describes a new computer–based model developed for the Electric Power Research Institute (EPRI) to quantify the emissions of chemical species in all gaseous, liquid and solid streams entering and leaving a plant. User–specified parameters allow the model to be tailored to a variety of power plant configurations and site–specific conditions. A unique feature of the model is that all parameters and input data may be characterized probabilistically so that uncertainties can be analyzed rigorously.

TABLE OF CONTENTS

II.   INTRODUCTION

The Clean Air Act Amendments (CAAA) of 1990 gave new importance to the control of hazardous air pollutants. Under previous Clean Air Act provisions (Section 112) hazardous pollutants were identified and regulated based on a determination of harm by the U.S. Environmental Protection Agency (EPA). To date, fewer than ten species have been regulated in this manner. Now, 189 chemical species have been named in the new CAAA provisions for air toxics (Title III). Control is required across a broad spectrum of industrial and other sources emitting 10 tons per year (tpy) or more of any one of the 189 listed substances, or 25 tpy or more of any combination of substances. The basis for regulation is the use of "maximum available control technology" (MACT). Additional controls could be required if EPA finds an unacceptable level of remaining risk to public health after MACT is applied.[1]

Electric utilities are not initially subject to these new air toxics requirements. Still, the CAAA requires EPA to perform a study of the hazards to public health reasonably anticipated to occur from emissions of hazardous air pollutants from electric steam generating units after the imposition of the other requirements of the 1990 Amendments. In the study report, due to Congress by November 15, 1993, EPA also must develop and describe alternate control strategies for hazardous emissions that may warrant regulation. EPA must regulate electric utilities under Title III if "appropriate and necessary" after considering the results of the study.

Two other studies required by the 1990 Amendments also may impact electric utilities. Sections 112(n)(1)(B) and (C) call for studies of mercury emissions from electric utilities and other sources. One of these studies will define threshold mercury exposure for adverse human health effects. The other study addresses the health and environmental effects of deposition of hazardous air pollutants in the Great Lakes, the Chesapeake Bay, Lake Champlain and U.S. coastal waters. If EPA concludes that further regulation is required because of either of these studies, then electric utilities could be included in the air toxics regulations.

The Electric Power Research Institute (EPRI) already has undertaken a program to study utility air toxics and their control. The EPRI program — known as PISCES (Power Plant Integrated Systems: Chemical Emissions Study) — has several major products and activities including, (1) a database of published information on trace species for conventional fossil fuel power plants; (2) a probabilistic computer model to estimate power plants emissions; (3) a field monitoring program to collect new data; (4) development of emission control technology selection guidelines; and (5) a sampling and analytical methods reference guide for trace chemical measurements. Descriptions of these and related EPRI activities appear elsewhere.[2–4]

III.   THE POWER PLANT ASSESSMENT MODEL

This paper focuses on the development and applications of the power plant chemical assessment model. The purpose of the model is to allow utilities to evaluate the performance of a given plant configuration with respect to multi–media emissions of chemical substances. The model provides estimates of the mass flow rates of all solid, liquid and gaseous streams emanating from the plant, including quantitative estimates of all trace species emissions.

A unique feature of the model is its ability to characterize uncertainties probabilistically. Any or all model input parameters can be assigned a probability distribution rather than a single value. The combined effect of all input uncertainties then is reflected in an uncertainty distribution for output parameters of interest obtained using Monte Carlo methods. Such distributions give the likelihood of a particular value, in contrast to conventional single–valued estimates. The model can be run using either deterministic values or uncertainty distributions yielding probabilistic results.

Descriptions of the initial model development and applications have been reported previously.[5, 6] Here we briefly summarize the model structure and design. Then, we elaborate on recent developments involving the user interface and linkage with the PISCES database.

A.   Model structure and data requirements

The model allows any fossil–fueled power plant to be configured for analysis. Version 1.0 is limited to conventional coal, oil and gas–fired plants employing any of the technologies listed in Table 1. Future versions will include additional environmental control technologies and a number of advanced power generation systems (e.g., fluidized beds, gasification combined cycle, etc.).

The model employs fundamental mass and energy balances to compute all system flow rates. Empirical data also are employed where necessary (e.g., in calculating nitrogen oxide emissions).

The underlying model is written in the Demos (Decision modelling system) computer language. This environment provides significant flexibility in configuring power plant designs while providing the capability to conduct probabilistic analyses. Documentation of the underlying model and the Demos computing environment can be found in other reference documents.[7–9] The model is designed to run on the Macintosh operating system.

Utilization of the model requires two types of data. One involves parameters specifying the power plant configuration and performance. The other involves data needed to evaluate the emissions of trace chemical substances. The latter includes information on the concentration of trace species in all plant inputs streams (including fuel, reagents, water and air), plus performance data characterizing how each chemical constituent in a given stream is "partitioned" or removed in various plant components or environmental control systems. If a probabilistic analysis is to be performed, plant characteristics, chemical species input quantities, and environmental control system performance characteristics also must be specified probabilistically. The PISCES database, discussed later, provides most of the information needed for trace species analysis.

B.   The graphical interface

To simplify the use of the model, a new interactive graphical interface has been developed that eliminates the need to master the underlying computer commands normally required for model operation. The graphical interface is a separate program that transmits appropriate

commands to the power plant model, and receives executed results for display. The interface program is written in Hypercard, which is a standard software accessory for Macintosh computers.

The complete software package thus involves interactions between three major components: Model, Interface and Database. Figure 1 shows a schematic of the interactions and inter–communications that are possible with the system inputs and outputs. This passing of messages, requests and results all happen simultaneously via the graphic interface to the model.

Figure 2 shows the interface screen used to begin model operation.

The model interface is divided into three sections: (1) configuring the power plant, (2) setting parameter values, and (3) getting results. These three operations appear near the top of the screen in Figure 2. Each operation is a "button" that can be activated (clicked on) with the computer mouse to move quickly to any of the three major sections of the model.

The first section of the model interface (Figure 2) displays the eight steps involved in configuring the power plant to be analyzed. Each of the eight boxes also is a button that calls up a more detailed menu of options to be selected. For example, clicking on "Flue Gas Cleanup" brings up the screen shown in Figure 3, where SO_2 and particulate control devices are chosen. The interface also is smart enough to prohibit the user from selecting options that are not permitted for technical reasons. Once the plant is configured the interface displays a schematic of the power plant and water system configurations to verify the intended designs. Finally, for trace species analysis, the user selects the species of interest from a graphical menu accessed through Button 8 in Figure 2.

The second section of the model interface requires setting parameter values for the ten major areas listed in Figure 4. The figure shows two columns requiring model parameter values. One column, labeled "Plant", contains parameters related to the overall plant performance and design. These parameters decide the major flow rates of materials through the power plant. For example, Figure 5 shows the screen for "Plant Performance" parameters, which include plant size and heat rate. The second column in Figure 4, labeled "Trace", refers to additional model parameters that

specify the behavior of trace species in a particular power plant section. The "Number of Cards" column shows those areas with more than one screen.

The final section of the interface is used to "Get Results." Figures 6a and 6b show examples of the "Plant" and "Water" diagrams from which results are obtained. Results may be displayed in graphical, tabular or diagrammatic form for individual power plant components. Or, the "Plant Summary" button in the center of Figure 6a can be activated to get overall results for plant inputs and outputs. Results for a particular device appear when clicking on the picture of that device. For example, the plant configuration in Figure 6a shows a coal pile, boiler, air preheater, ESP, wet FGD system, stack, bottom ash pond and landfill disposal system. These are separate "buttons" that can be activated to get results for that particular component of the plant.

C.   Probabilistic analysis capability

As noted earlier, a unique feature of the power plant chemical assessment model is its ability to analyze uncertainties probabilistically. Probability distributions are assigned to any plant or trace input parameter using the "Uncertainty" button at the bottom of each parameter input screen. For example, Figure 7 shows the result of choosing "Uncertainty" for the "Plant Performance" card shown earlier in Figure 5. At this point, any parameter on the card can be specified probabilistically by activating the "Edit" button. This brings up the screen illustrated in Figure 8. A pop–up menu allows various types of uncertainty distributions to be entered.

Once all parameter uncertainties are assigned, the "Get Results" screen allows the sampling procedure (Monte Carlo or Latin Hypercube sampling) to be selected, with the desired number of iterations. The combined effect of all uncertain parameters is then evaluated using stochastic simulation methods. Full details of the model operation are described in a comprehensive user's manual.[10]

IV.   THE PISCES CHEMICAL DATABASE

Another major element of the PISCES study is the development and compilation of published and other data regarding chemical substances found in streams from conventional and

fossil fuel power systems.[11,12] This database has been developed by Radian Corporation and implemented in a database management system operating on a Sun3 computer workstation. For the chemical assessment model, information from the PISCES database has been downloaded, parsed and restructured for compatibility with the computer model interface. Data files for 33 selected trace species, listed in Table 2, have been created. These species represent key chemicals of potential concern to utilities. The computer model interface can track up to 25 of these species in a single model run.

A.   Species data files

Frequency distributions for the 33 species have been developed for each trace species input parameter required by the model. There are three types of trace species input parameters: (1) the concentrations of trace species in power plant input streams (i.e., fuel, reagents, water and air); (2) the concentrations of new trace species created within the power plant (e.g., trace organics); and (3) the partitioning of trace species across various power plant components. In all, there are 33 model input parameters for each trace species, as shown in Table 3.[a] This table sorts the 33 parameters into the 10 major categories listed on the "Set Parameters" check list screen shown earlier in Figure 4. Note that only a subset of these parameters is used for any given model run. The overall database files, however, contain over a thousand distributions (33 parameters times 33 species). At present, many of these are placeholders awaiting additional data.

B.   Interface access to the database

Data distributions for each trace species and each model input parameter can be quickly and easily imported to the model directly from data files on the computer. Database retrieval buttons on each trace parameter input screen, shown in Figure 9, are used to perform this task.

Frequency distributions for each model parameter were derived by sorting the data from the full PISCES database on five criteria: (1) fuel type, (2) boiler type, (3) FGD reagent type, (4) device type and (5) unit name. Not all five criteria were used for each parameter; the particular

---

[a] If is merely coincidence that there are both 33 species and 33 parameters.

sort criteria depended upon what was technically appropriate and how much data were available in the PISCES database. The "Options" button seen in Figure 9 is used to display the sort criteria for which data sets are available. Then, the data for that set of criteria can be imported using the "Retrieve" button.

The database files for each parameter contain frequency distributions for all 33 species. When data are retrieved, however, only the frequency distributions for those species chosen for an analysis are imported. The "sort criteria" selection further narrows the subset of available data imported to the model. Once entered, this data can be easily edited or modified using the computer model interface. User–specified data also can be entered in lieu of the PISCES data files. Indeed, in instances where the PISCES database does not yet contain parameter information for a particular species, user–specified data are required.

A reference data book summarizes all the PISCES data distributions used for the model interface data files.[13] It also tabulates the results of data sorts for each model parameter and each trace substance. Updates to this databook are planned for late 1991.

V.   MODEL APPLICATIONS

Any assessment of control strategies or environmental risks for hazardous air pollutants must begin with a characterization of source emissions. Species emission estimates may provide a basis for determining regulatory compliance (e.g., whether emissions exceed some specified value), or may provide input to more comprehensive assessments of effects and risks (such as called for in special studies under the 1990 CAAA). The ability of control technology, fuel choice and other plant design parameters to affect the emission rates of hazardous pollutants (not only to the atmosphere, but also to water and land) can then be examined where problems are found to exist. The capability to quantify uncertainties is important for judging the robustness of results and the degree of confidence in proposed solutions.

Applications to date of the power plant chemical assessment model have included, (1) deterministic studies of ten power plant configurations to benchmark key performance results

against independent studies by Bechtel Corporation;[14] (2) illustrative probabilistic studies using early versions of the PISCES database;[5,6] (3) one study of trace species emissions from a European power plant;[15] and (4) six utility–specific case studies carried out as part of the beta–testing of the model. Additional case studies are planned for several power plants visited in EPRI's data acquisition program under PISCES.[3]

Here we present an illustrative example of how the model may be used to quantify hazardous air emissions from a coal–fired power plant equipped with a cold–side electrostatic precipitator (ESP) and a wet limestone FGD system (the configuration shown earlier in Figure 6a). For convenience, we use the model default parameters for each device, which are based on studies by Bechtel.[14] A set of 19 trace species is selected for illustrative purposes.

The key plant performance parameters are those shown earlier in Figure 5. Figures 10 and 11 show two additional input screens for the fuel type and FGD system characteristics, respectively. Figures 12a and 12b show the median values of trace species in coal and an example frequency distribution for bituminous coal, based on the PISCES database.

A summary table of median input and output flows of the selected trace species is shown in Figure 13. For any plant component of interest more detailed results can be obtained as described earlier. For example, Figures 14 and 15, respectively, show the median performance characteristics and trace species flows for the FGD system. Figures 16 and 17 show the probabilistic results for one species (arsenic) exiting the FGD unit. Both graphical and tabular results are displayed. These two figures show that while the median hourly flow of arsenic is 8.1×10^{-4} lb/hr there is a 10 percent chance (90 percent cumulative probability) it could be as high as 3.2×10^{-3} lb/hr. Flow rates that are judged to be unacceptably high become candidates for control strategies in subsequent analyses.

VI.   CONCLUSION

The power plant chemical assessment model developed as part of the EPRI PISCES program offers a unique capability for evaluating and managing hazardous air pollutant emissions from

electric power plants. The model's user–friendly graphical interface and ability to rigorously evaluate uncertainties make it a powerful analytical tool for general and site–specific studies. The PISCES database is a key complement to the model, offering a rich source of data on trace species quantities and behavior.

As of this writing, Version 1.1 of the model is undergoing beta–testing by six utilities in North America and Europe. The results of that testing will be incorporated in an updated release of the model in late 1991. Subsequent enhancements are scheduled for 1992.

The PISCES database also is being revised and updated under the management of Radian Corporation. A revised version of the database compatible with the plant computer model is expected by late 1991. Subsequently, the database will be expanded to incorporate new data from the EPRI field sampling program.

VII.   ACKNOWLEDGEMENTS

VIII.   REFERENCES

1. Public Law 101–549, November 15, 1990.
2. **Boutacoff, D.**, New Focus on Air Toxics, *EPRI Journal*, 16, 4, 1991.
3. **Chow, W.**, PICSES: Managing Air Toxics, *ECS Update*, 21, 2, 1991.
4. **Chow, W., Miller, M. J., Fortune, J., Behrens, G. and Rubin, E. S.**, Managing Air Toxics Under the New Clean Air Act Amendments, *Power Engineering*, 1991.
5. **Rubin, E. S., Salmento, J. S. and Chow, W.**, A Probabilistic Approach to Multimedia Environmental Management, Paper No. 90–131.2, presented at the 1990 AWMA Annual Meeting, AWMA, Pittsburgh, PA, 1990.
6. **Rubin, E. S., Salmento, J. S. and Chow, W.**, Chemical Characterization of Power Plant Waste Streams, Paper No. 90–37.1, presented at the 1990 AWMA Annual Meeting, Air and Waste Management Association, Pittsburgh, PA, 1990.
7. **Wishbow, N. and Henrion, M.**, *An Introductory Tutorial for Demos*, Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, PA, 1985.
8. **Henrion, M. and Wishbow, N.**, *Demos User's Manual: Version Three*, Carnegie Mellon University, Department of Engineering and Public Policy, Pittsburgh, PA, 1987.
9. **Arnold, B. and Henrion, M.**, *Demos Interface Manual* (Draft), Department of Engineering and Public Policy, Carnegie Mellon University, November, 1990.
10. **Berkenpas, M. B. and Rubin, E. S.**, *Power Plant Chemical Assessment Model: User Documentation* (Draft), prepared for the Electric Power Research Institute, Palo Alto,

CA, by Center for Energy and Environmental Studies, Carnegie Mellon University, Pittsburgh, PA, April, 1991.

11. **Balfour, W. D., Chow, W. and Rubin, E. S.**, PISCES: A Utility Database for Assessing the Pathways of Power Plant Chemical Substances, Paper No. 89-71.6, presented at the 1989 AWMA Annual Meeting, Air & Waste Management Association, Anaheim, CA, 1989.

12. **Behrens, G. P. and Chow, W.**, Use of A Multi–Media Database for Chemical Emission Studies of Conventional Power Systems, Paper No. 90-131.1, presented at the 1990 AWMA Annual Meeting, Air & Waste Management Association, Pittsburgh, PA, 1990.

13. **Berkenpas, M. B., Zalevsky, K. and Rubin, E. S.**, *Power Plant Chemical Assessment Model: PISCES Database Book* (Draft), prepared for the Electric Power Research Institute, Palo Alto, CA, by Center for Energy and Environmental Studies, Carnegie Mellon University, Pittsburgh, PA, April, 1991.

14. **Bechtel Group Inc.**, *Power Plant Integrated Systems: Chemical Emission Studies* (*PISCES*), prepared for Electric Power Research Institute, Palo Alto, CA, by Bechtel Group Inc., February, 1989.

15. **Rubin, E. S., Salmento, J. S. and Chow, W.**, Evaluating Power Plant Control Strategies for Air Toxics, Paper No. 91-103.20, presented at the 1991 AWMA Annual Meeting, Air & Waste Management Association, Vancouver, British Columbia, 1991.

IX.   TABLES

TABLE 1. Current technology options in the power plant model and interface

Fuel Characteristics	**Solid Waste Disposal**
• Coal	• Landfill
• Oil	• Ponding
• Gas	• Co–Disposal
Boiler Systems	**Cooling Water System**
• Tangential	• Once–Through
• Wall	• Cooling Tower
• Cyclone	• Pond or Lake
	• Fresh or Saline
Particulate Controls	**Water Treatment Systems**
• Precipitator	• Plant Makeup Water
• Fabric Filter	• Plant Service Water
	• Boiler Makeup
SO$_2$ Controls	• Condensate Polisher
• Wet Lime FGD	• Cooling Tower Makeup
• Wet Limestone FGD	• Tower Slip Stream
• Lime Spray Dryer	• Ash Pond Discharge

TABLE 2. Selected trace species for the model database

Ammonia	Chrysene	Mercury
Arsenic	Cobalt	Molybdenum
Barium	Copper	Naphthalene
Benzene	Cyanide	Nickel
Benzo–pyrene	Fluoride	Phosphate
Beryllium	Fluorine	Phosphorus
Cadmium	Formaldehyde	Pyrene
Chloride	HCl	Radium 226
Chlorine	HF	Selenium
Chromium	Lead	Toluene
Chromium–6	Manganese	Vanadium

TABLE 3. Model input parameters for trace species

Trace Species Parameter	Description of Parameter	Units
Fuel Properties		
Coal	Concentration of Trace Species in Coal	ppmw
Oil	Concentration of Trace Species in Oil	ppmw
Natural Gas	Concentration of Trace Species in Natural Gas	ppmw
Coal Pile Runoff	Concentration of Trace Species in Coal Pile Runoff Water	ppmw
Pyrite Rejects	Concentration of Trace Species in Pyrite Removed from Coal Pulverizer	ppmw
Plant Performance		
Ambient Air	Concentration of Trace Species in Ambient Air	ppmw
Furnace Partition	Ratio of Species Concentrations: (In Coal)÷([In Bottom Ash]x[Ash in Coal])	fraction
Steam Cycle and Condenser		
Boiler Cleaning Wastes	Concentration of Trace Species in Boiler Chemical Cleaning Waste	ppmw
Furnace Emission Factors		
Furnace Emissions	Concentration of Molecular Species Created Inside Furnace	ppmw
Fireside Cleaning Wastes	Concentration of Trace Species in Fireside Cleaning Waste	ppmw
Air Preheater Cleaning Wastes	Concentration of Trace Species in Air Preheater Cleaning Waste	ppmw
Particulate Removal		
ESP Partition	Ratio of Species Concentration: (Removed from ESP)÷([Into ESP]x[TSP Efficiency])	fraction
FF Partition	Ratio of Species Concentration: (Into FF–Out of FF)÷([Into FF]x[TSP Efficiency])	fraction
Flue Gas Desulfurization		
Limestone	Concentration of Trace Species in Limestone	ppmw
Lime	Concentration of Trace Species in Lime	ppmw
Wet Lime/Limestone Partition	Ratio of Species Concentration: (Into FGD–Out of FGD)÷(Into FGD)	fraction
Solid Waste Disposal		
Bottom Ash Disposal Leachate Partition	Ratio of Species Concentration: (Water Overflowing Pond)÷(Solids Entering Pond)	fraction
Quench Evaporation Partition	Ratio of Species Concentration: (Evaporated from Sluice Water)÷(In Sluice Water)	fraction
Water Overflow Partition	Ratio of Species Concentration: (Water Overflow Disposal)÷(Solids Into Disposal)	fraction
Fly Ash Disposal Leachate Partition	Ratio of Species Concentration: (Leachate Exiting Disposal)÷(Solids Into Disposal)	fraction
Cooling Water System		
Fresh Water	Concentration of Trace Species in Fresh Water	ppmw
Saline Water	Concentration of Trace Species in Saline Water	ppmw
Once–Through Emissions	Concentration of Molecular Trace Species Created Inside Cooling Water System	ppmw
Tower Evaporation Partition	Ratio of Species Concentration: (Evaporated)÷(In Recirculating Water)	fraction
Basin Sludge	Concentration of Trace Species in Cooling Tower Basin Sludge	ppmw
Water Treatment Systems		
Plant Makeup Water Partition	Ratio of Species Concentration: (Removed from Plant)÷(Into Plant)	fraction
Zero Discharge Partition	Ratio of Species Concentration: (Removed from Plant)÷(Into Plant)	fraction
Domestic Water Partition	Ratio of Species Concentration: (Removed from Plant)÷(Into Plant)	fraction
Tower Makeup Partition	Ratio of Species Concentration: (Removed from Plant)÷(Into Plant)	fraction
Tower Slip Partition	Ratio of Species Concentration: (Removed from Plant)÷(Into Plant)	fraction
Demineralizer Partition	Ratio of Species Concentration: (Removed from Demin.)÷(Entering Demin.)	fraction
Wastewater Partition	Ratio of Species Concentration: (Removed from Plant)÷(Into Plant)	fraction
Floor and Yard Drains	Concentration of Trace Species in Floor and Yard Drain Waste	ppmw

X.   FIGURE CAPTIONS

Figure 1.   Interaction and communications between the model interface, PISCES database, and model.

Figure 2.   The "Configure Plant" checklist is the first of three major sections of the model. Eight plant areas can be reached from here.

Figure 3.   Sulfur and particulate removal devices are configured on this screen.

Figure 4.   The second checklist has ten major sections and two types of parameters. These twenty elements contain all model input parameter lists.

Figure 5.   Parameters on this screen determine the primary flow rates.

Figure 6.   These screens are used to obtain results for (a) solid and gaseous streams and (b) plant water streams.

Figure 7.   The "Uncertainty" button is used to enter frequency distribution data for any model parameter.

Figure 8.   The uncertainty editor builds a distribution for a selected parameter. A pop-up menu contains various options.

Figure 9.   Each trace input screen can access the PISCES database files using the area at the bottom–right corner of the screen.

Figure 10.   This screen provides an ultimate analysis of the selected fuel.

Figure 11.   Input parameters for the lime/limestone FGD system are listed on this screen.

Figure 12.   Trace species in coal may be entered automatically from the PISCES database, or manually using the graphical interface.

Figure 13.   Median values of trace species flow rates are summarized for (a) streams entering and (b) streams exiting the power plant.

Figure 14.   Median values of FGD flow rates, temperatures and other data are shown in diagram form using the "Plant" button.

Figure 15.   Median values of FGD flow rates are show in table form for the chosen trace species using the "Trace" button.

Figure 16.   A cumulative probability distribution of the arsenic flow rate exiting the FGD system.

Figure 17.　　A tabular summary of the cumulative probability distribution for arsenic exiting the FGD system.

XI.   FIGURES
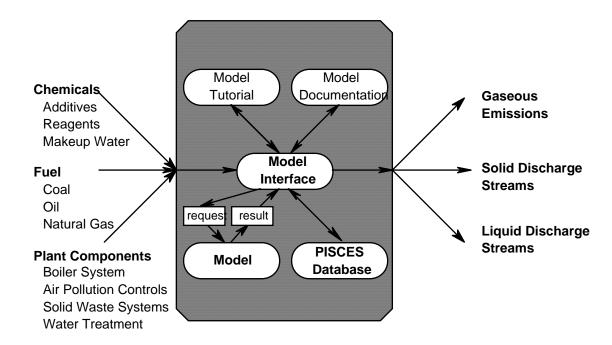
Figure 1
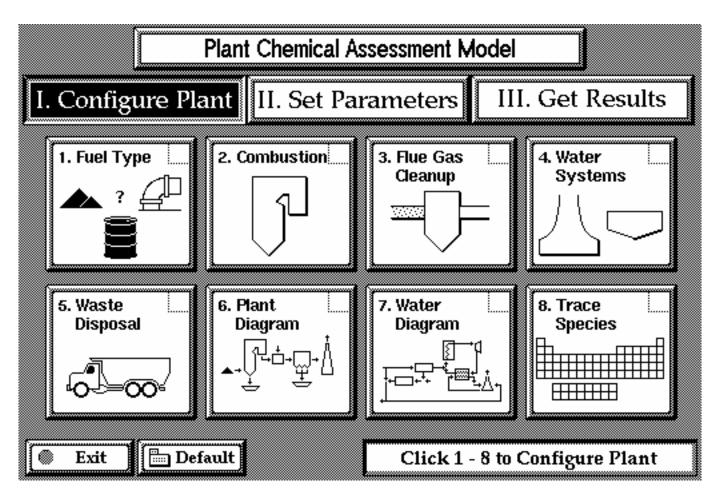
Figure 2
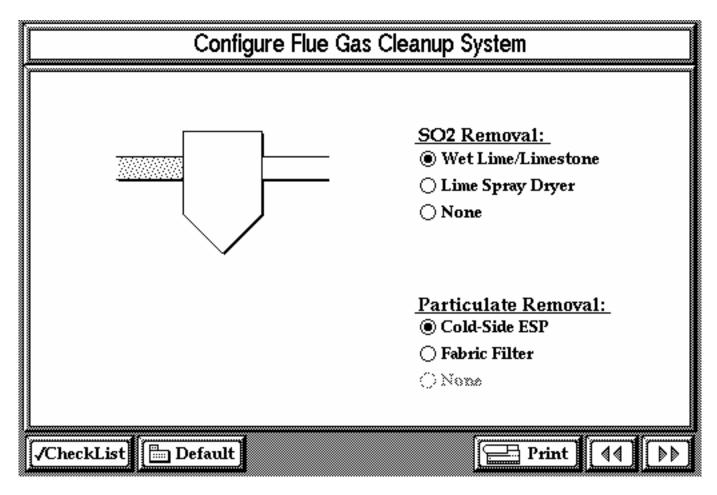
Figure 3
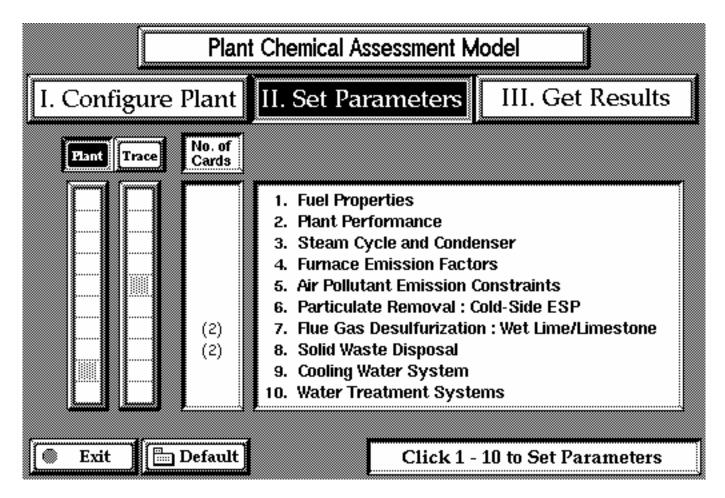
Figure 4

Plant Performance Input Parameters

Parameter Description	Units	Value	Calc	Minimum	Maximum	Default
Gross Electrical Output	(MWg)	540		100	1000	540
Steam Cycle Heat Rate	(Btu/kWh)	7880		6000	10000	7880
Capacity Factor	(%)	75		15	100	75
Excess Air for Furnace	(%)	20		5	30	20
Leakage Air at Preheater	(%)	19		0	40	19
Air Temperature	(°F)	80		60	110	80
Air Pressure	(psia)	14.7		12	15	14.7
Specific Humidity	(lb H2O/lb dry air)	0.018		0	0.03	0.018
Boiler Efficiency	(%)		☒	80	95	Calc
Unaccounted Losses in Boiler	(%)	0.5		0	1	0.5
Temperature Exiting: Economizer	(°F)	700		600	800	700
Preheater	(°F)	300		250	400	300
Energy Pulverizers	(%MWg)	0.6		0	1	0.6
Penalties: Steam Pumps	(%MWg)	0.65		0.5	0.7	0.65
(Excluding FD Fans	(%MWg)	1.5		0.7	4	1.5
Gas Cleanup Cooling System	(%MWg)	0.4		0.4	2	0.4
Systems) Misc.	(%MWg)	1.3		0	2	1.3

| √CheckList | 🖳 Default | ◉ Value ○ Uncertainty | 🖨 Print | ◀◀ | ▶▶ |

Figure 5
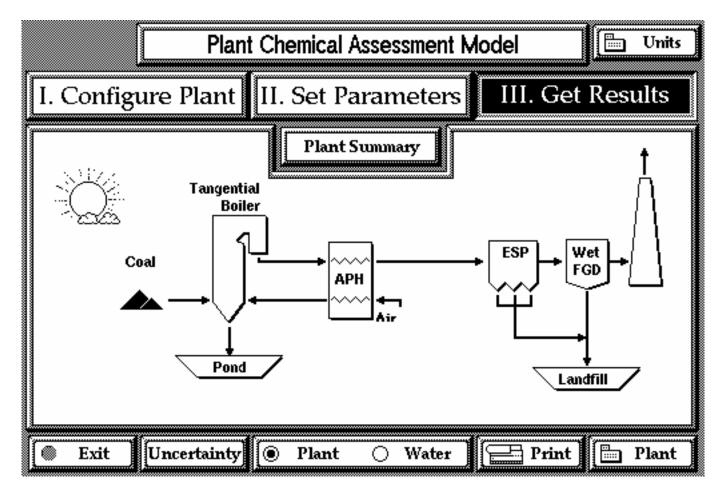
Figure 6(a)
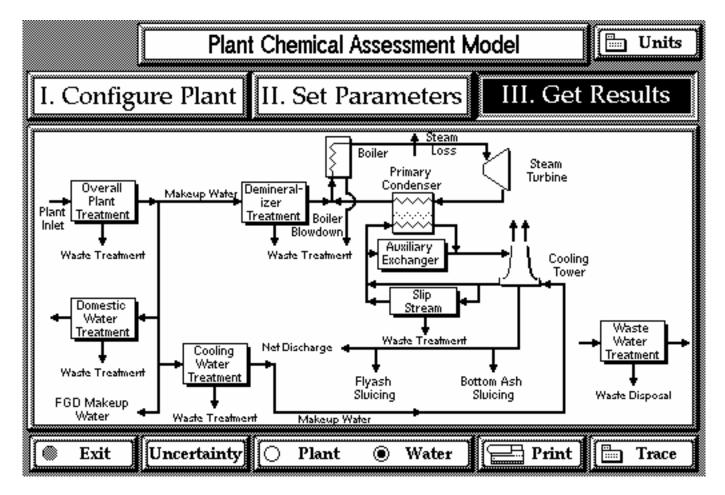
Figure 6(b)

Plant Performance Input Parameters

Parameter Description	Units + / *	Uncertainty	Edit
Gross Electrical Output	(MWg)		○
Steam Cycle Heat Rate	(Btu/kWh)		○
Capacity Factor	(%)		○
Excess Air for Furnace	(%)		○
Leakage Air at Preheater	(%)		○
Air Temperature	(°F)		○
Air Pressure	(psia)		○
Specific Humidity	(lb H2O/lb dry air)		○
Boiler Efficiency	(%)		○
Unaccounted Losses in Boiler	(%)		○
Temperature Exiting: Economizer	(°F)		○
Preheater	(°F)		○
Energy Pulverizers	(%MWg)		○
Penalties: Steam Pumps	(%MWg)		○
(Excluding FD Fans	(%MWg)		○
Gas Cleanup Cooling System	(%MWg)		○
Systems) Misc.	(%MWg)		○

| √CheckList | 🖳 Default | ○ Value ◉ Uncertainty | 🖵 Print | ◀◀ | ▶▶ |

Figure 7

Figure 8

Particulate Removal — ESP Partition					

Ratio of Species Mass Conc. : (Removed from ESP) ÷ ([Into ESP] x [TSP Efficiency])   (fraction)

Trace Species	Median Value	Default	Trace Species	Median Value	Default
Arsenic	0.98674	0	Selenium	0.82593	0
Barium	0.99086	0	Toluene	0	0
Benzo-pyrene	0.44444	0	Vanadium	0.99149	0
Cadmium	0.81649	0			
Chloride	0.34358	0			
Chromium	0.98081	0			
Cobalt	0.99197	0			
Copper	0.98894	0			
Fluoride	0.30047	0			
Lead	0.96463	0			
Manganese	0.99153	0			
Mercury	0.26814	0			
Molybdenum	0.98420	0			
Naphthalene	0	0			
Nickel	0.99214	0			
Phosphorous	0	0			

	Sort Criteria	Last Search	Current Search
	Fuel Type	Bituminous	Bituminous
	Unit Name	All Units	All Units

Options Retrieve

√CheckList Default ⦿ Value ○ Uncertainty Print ◀◀ ▶▶

Figure 9

Fuel Property Input Parameters

Fuel Type: ▲▲

Coal

Coal Name: ▭ Illinois #6

Rank: Bituminous

	HHV	Carbon	Hydrogen	Oxygen	Sulfur	Nitrogen	Ash	Moisture
	Btu/lb			Weight Percent, as Fired				
ROM Coal	10194	56.95	3.70	7.19	4.36	1.12	14.38	12.30

√CheckList   ▭ Default   🗑 Delete   🗁 Save   🖨 Print   ◀◀   ▶▶

Figure 10

Wet FGD Input Parameters

Parameter Description	Units	Value	Calc	Minimum	Maximum	Default
Maximum SO2 Removal Efficiency	(%)	95		90	98	95
Actual SO2 Removal Efficiency	(%)	▨	⊠	30	98	Calc
Particulate Removal Efficiency	(%)	50		0	100	50
Reagent Stoichiometry	(moles Ca/moles S)	1.15		1	3	1.15
Maximum Absorber Size	(1000 acfm)	425		100	1000	425
Number of Operating Absorbers		▨	⊠	1	10	Calc
Number of Spare Absorbers		▨	⊠	0	3	Calc
Temperature Rise Across ID Fan	(°F)	14		0	25	14
Gas Temp. Exiting Scrubber	(°F)	▨	⊠	125	185	Calc
Gas Temp. After Reheater	(°F)	178		110	225	178
Oxidation of CaSO3 to CaSO4	(%)	90		0	100	90
Entrained Water Past Demister	(% Evap.)	0.79		0.25	1	0.79
Gas Pressure Exiting FGD	(Inches W.G.)	4		4	10	4
Reagent Purity	(wt %)	92.4		80	100	92.4
Water Content of Reagent	(wt %)	0		0	5	0
Reagent Slurry Water	(lb H2O/lb reag.)	3.67		0	10	3.67
Demister Water Usage	(lb H2O/lb reag.)	0		0	10	0
Energy Penalty	(% MWg)	▨	⊠	0	5	Calc

√CheckList   ▤ Default   ⦿ Value ○ Uncertainty   ▤ Print   ◀◀   ▶▶

Figure 11

Fuel Properties — Coal						

Concentration of Trace Species in Coal (ppmw)

Trace Species	Median Value	Default	Trace Species	Median Value	Default
Arsenic	8.71665	0	Selenium	3.21665	0
Barium	99.37963	0	Toluene	0	0
Benzo-pyrene	0.33500	0	Vanadium	34.47325	0
Cadmium	0.40000	0			
Chloride	604.8	0			
Chromium	17.12325	0			
Cobalt	5.97857	0			
Copper	20.28889	0			
Fluoride	119.0	0			
Lead	9.05916	0			
Manganese	62.53330	0			
Mercury	0.20250	0			
Molybdenum	1.43325	0			
Naphthalene	1.83000	0			
Nickel	18.00000	0			
Phosphorous	72.00668	0			

	Sort Criteria	Last Search	Current Search
	Coal Rank	Bituminous	Bituminous
	Unit Name	All Units	All Units

[ ]Options   Retrieve

√CheckList   [ ] Default   ◉ Value ○ Uncertainty   Print   ◀◀   ▶▶

Figure 12

Species	Air Into Furnace	Fuel Into Furnace	Furnace Factors	Intermit. Cleaning Streams	Lime/ Limestone Reagent	Fresh Makeup Water	Saline Cooling Water	Cooling Water Factors	Rainfall Runoff	Total Into Plant
Arsenic	0	4.123	0	0	0.07	132.9	0	0	384u	137.1
Barium	0	46.99	0	0	2.102	1197	0	0	1.69m	1246
Benzo-pyrene	256n	0.158	0	0	0	0.292	0	0	0	0.451
Cadmium	0	0.222	0	0	0.067	0.665	0	0	29.5u	0.954
Chloride	0	285.9	0	0	3.504	5384	0	0	1.012	5675
Chromium	0	8.097	0	0	0.701	7.312	0	0	84.3u	16.11
Cobalt	0	2.827	0	0	0	66.47	0	0	422u	69.3
Copper	0	9.593	0	0	0.224	4.155	0	0	4.17m	13.98
Fluoride	0	56.26	0	0	8.199	58.5	0	0	4.26m	123
Lead	0	4.286	0	0	0.911	15.16	0	0	0	20.35
Manganese	0	29.58	0	0	3.083	11.87	0	0	0.089	44.61
Mercury	0	0.096	0	0	841u	0.226	0	0	21.1u	0.323
Molybdenum	0	0.678	0	0	0.14	598.2	0	0	190u	599.1
Naphthalene	6.17m	0.865	0.241	0	0	0	0	0	0	1.112
Nickel	0	8.51	0	0	0.302	9.173	0	0	9.53m	18
Phosphorous	0	34.1	0	0	7.01m	7.378	0	0	1.69m	41.49
Selenium	0	1.521	0	0	0.035	2.526	0	0	50.6u	4.082
Toluene	0	0	0	0	0	0	0	0	0	0
Vanadium	0	16.3	0	0	1.261	13.29	0	0	498u	30.86
Total	6.17m	510.1	0.241	0	20.61	7509	0	0	1.124	8041

Overall Trace Entering | **Overall Trace Flow Rate** lbs/hr | Units

Return | Key: m = 1.0e-3 u = 1.0e-6 n = 1.0e-9 p = 1.0e-12   K = 1.0e+3 M = 1.0e+6 B = 1.0e+9 T = 1.0e+12 | Print | Trace

Figure 13(a)

Overall Trace Exiting | **Overall Trace Flow Rate** | lbs/hr | **Units**

Species	Stack Gas	Bottom Ash Evaporation	Tower Drift & Evaporation	Ash Pond Residue	Ash Pond Leach	Flue Gas Waste Remain	Flue Gas Waste Leach	Net Cool Water Out	Domestic Water Dischg	Waste Water Dischg	Waste Water Evaporation	Waste Water Sludge	Remove Offsite	Total Out Plant
Arsenic	750u	0	0	0.079	37.8u	4.732	0	132.2	0.036	0.101	0	2u	0	137.1
Barium	3.38m	0	0	3.719	340u	44.93	0	1190	0.32	0.905	0	398u	0	1246
Benzo-pyrene	0.158	0	0	41.2u	83.2n	1.32m	0	0.291	78.3u	0	0	221u	0	0.451
Cadmium	146u	0	0	0.042	189n	0.25	0	0.661	178u	531u	0	872n	0	0.954
Chloride	107.4	0	0	1.058	1.53m	206	0	5354	1.441	3.297	0	1.783	0	5675
Chromium	86.4u	0	0	2.133	2.08u	6.698	0	7.27	1.36m	5.61m	0	1.12u	0	16.11
Cobalt	9.89m	0	0	0.423	18.9u	2.703	0	66.09	0.018	0	0	0.051	0	69.3
Copper	0.045	0	0	1.935	1.18u	7.857	0	4.131	1.11m	7.31m	0	3.66u	0	13.98
Fluoride	8.545	0	0	13.34	16.6u	42.85	0	58.16	0.016	0	0	0.048	0	123
Lead	104u	0	0	0.232	4.31u	4.976	0	15.07	4.06m	0.011	0	1.03u	0	20.35
Manganese	1.33m	0	0	7.441	3.37u	25.27	0	11.8	3.17m	0.097	0	36.1u	0	44.61
Mercury	0.032	0	0	2.97m	64.3n	0.062	0	0.225	60.5u	0	0	192u	0	0.323
Molybdenum	3.9m	0	0	0.148	170u	3.446	0	594.9	0.16	0.452	0	163u	0	599.1
Naphthalene	1.112	0	0	0	0	0	0	0	0	0	0	0	0	1.112
Nickel	1.2m	0	0	2.046	2.61u	6.807	0	9.121	2.45m	0.016	0	2.47u	0	18
Phosphorous	32.23	0	0	1.867	2.1u	0.04	0	7.337	1.97m	7.26m	0	1.23u	0	41.49
Selenium	0.606	0	0	0.039	718n	0.922	0	2.512	676u	1.96m	0	921n	0	4.082
Toluene	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vanadium	721u	0	0	2.994	3.78u	14.63	0	13.22	3.56m	0.011	0	1.69u	0	30.86
Total	150.1	0	0	43.56	2.14m	372.2	0	7466	2.003	4.914	0	1.883	0	8041

Return

Key m=1.0e−3 u=1.0e−6 n=1.0e−9 p=1.0e−12
K=1.0e+3 M=1.0e+6 B=1.0e+9 T=1.0e+12

Print   **Trace**

Figure 13(b)

Figure 14

| Wet FGD System | | | | Trace Species Flow Rate (lbs/hr) | | | | Units |

Species	Flue Gas In	Reagent Inject	Water Inject	Flue Gas Bypass	Total Remove	Dewater Waste	Waste to Dispose	Flue Gas Out	Flue Gas Bypass Remix
Arsenic	0.071	0.07	0.599	0	0.739	0	0.739	750u	750u
Barium	0.147	2.102	5.392	0	7.637	0	7.637	3.98m	3.98m
Benzo-pyrene	0.158	0	1.32m	0	1.32m	0	1.32m	0.158	0.158
Cadmium	0.024	0.067	3m	0	0.094	0	0.094	146u	146u
Chloride	204.6	3.504	24.26	0	125	0	125	107.4	107.4
Chromium	0.029	0.701	0.033	0	0.762	0	0.762	86.4u	86.4u
Cobalt	9.89m	0	0.3	0	0.3	0	0.3	9.89m	9.89m
Copper	0.045	0.224	0.019	0	0.243	0	0.243	0.045	0.045
Fluoride	29.5	8.199	0.264	0	29.42	0	29.42	8.545	8.545
Lead	0.022	0.911	0.068	0	1.001	0	1.001	104u	104u
Manganese	0.091	3.083	0.053	0	3.227	0	3.227	1.33m	1.33m
Mercury	0.081	841u	1.02m	0	0.051	0	0.051	0.032	0.032
Molybdenum	3.3m	0.14	2.696	0	2.836	0	2.836	3.3m	3.3m
Naphthalene	1.112	0	0	0	0	0	0	1.112	1.112
Nickel	0.031	0.302	0.041	0	0.373	0	0.373	1.2m	1.2m
Phosphorous	32.23	7.01m	0.033	0	0.04	0	0.04	32.23	32.23
Selenium	0.606	0.035	0.011	0	0.046	0	0.046	0.606	0.606
Toluene	0	0	0	0	0	0	0	0	0
Vanadium	0.058	1.261	0.06	0	1.378	0	1.378	721u	721u
Total	268.8	20.61	33.84	0	173.2	0	173.2	150.1	150.1

Return   ○ Diagram   ◉ Table   Print   Trace

Figure 15

Figure 16

Arsenic Rate in Flue Gas out Wet FGD (lbs/hr)

0%	28.8u
5%	65.9u
10%	100u
20%	369u
30%	499u
40%	695u
50%	811u
60%	929u
70%	1.23m
80%	1.57m
90%	3.21m
95%	5.7m
100%	0.021
Mean	1.94m
Std. Dev.	4.08m

Return   ○ Cdf ○ Pdf ◉ Statistics   Print

Figure 17