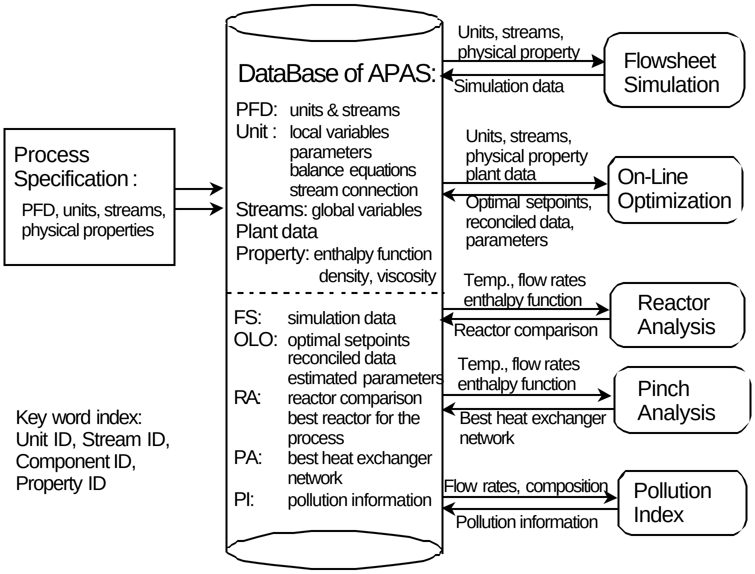
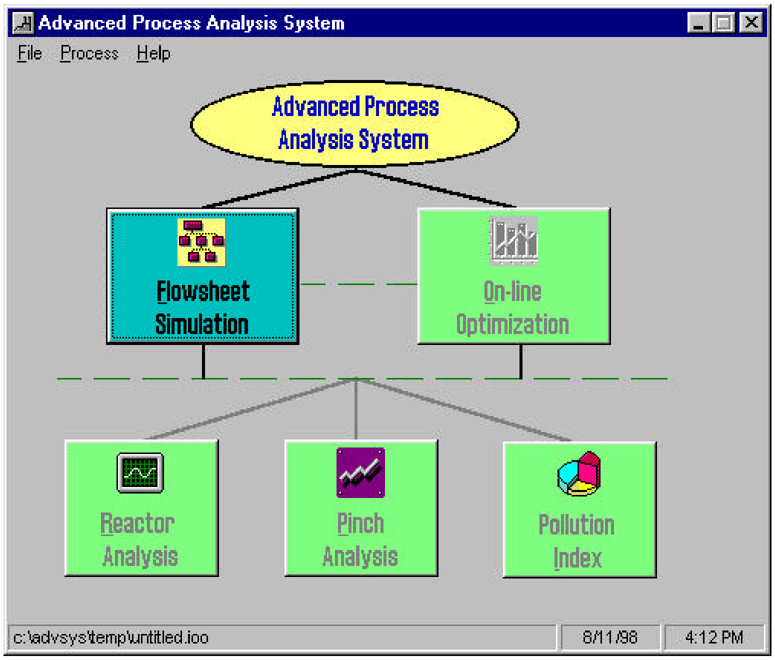


Mineral Processing Research Institute

Louisiana State University

Advanced Process Analysis System

User's Manual
and
Tutorial
for the Contact Process
for Sulfuric Acid



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I. INTRODUCTION AND METHODOLOGY

An Advanced Process Analysis System is a powerful tool for use by process and plant engineers to perform comprehensive and in-depth evaluations of economic, environmental, safety and hazard analysis projects. This system is based on chemical engineering fundamentals such as stoichiometry, thermodynamics, fluid dynamics, heat transfer, mass transfer, reactor design and optimization. It helps to identify pollutants in chemical processes and petroleum refineries and develop innovative, economically viable designs to eliminate their generation. It aims at waste minimization and pollution prevention in chemical plants, in addition to increased profit and improved efficiency of operations.

The framework of the Advanced Process Analysis System is shown in Figure 1. The main components of this system are an on-line optimization program, a flowsheeting program for process material and energy balances, a chemical reactor analysis program, a heat exchanger network design program, and a pollution assessment module. A Windows interface is used to integrate these programs into one user-friendly application.

The Advanced Process Analysis System methodology to identify and eliminate the causes of energy inefficiency and pollutant generation is based on the onion skin diagram shown in Figure 2. Having an accurate description of the process from on-line optimization, an evaluation of the best types of chemical reactors is done first to modify and improve the process. Then the separation units are evaluated. This is followed by the pinch analysis to determine the best configuration for the heat exchanger network and determine the utilities needed for the process. Not shown in the diagram is the pollution index evaluation, which is used to identify and minimize emissions. The following gives a detailed description of the Advanced Process Analysis System and its components, and how they are used together to control and modify the process to maximize the profit and minimize the wastes and emissions. The IMC Agrico's contact process will be used to demonstrate the use and capabilities of the Advanced Process Analysis System. This will follow the description of the programs and the components.

A. Flowsheeting

The first step towards implementing the Advanced Process Analysis System is the development of the process model using Flowsim. As described earlier, process model is a set of constraint equations, which are the material and energy balances, rate equations and equilibrium relations that describe the material and energy transport and the chemical reactions of the process. These form a mathematical model of relationships between the various plant units and process streams. Formulation of the process model can be divided into two important steps.

A-1. Formulation of Constraints for Process Units

The formulation of constraints can be classified into empirical and mechanistic methods. The process models used in Advanced Process Analysis System belong to the type of

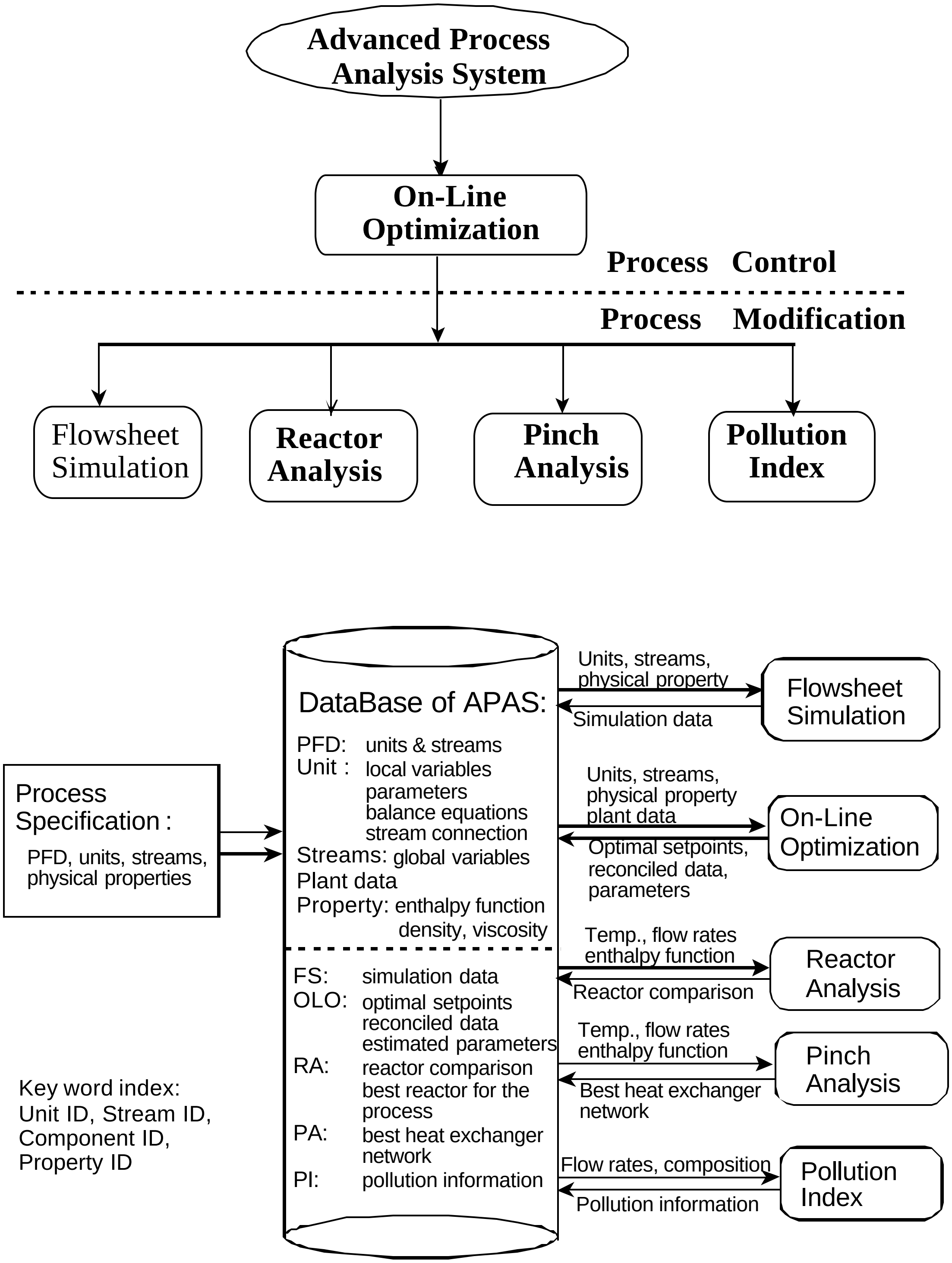


Figure 1: The Framework of the Advanced Process Analysis System

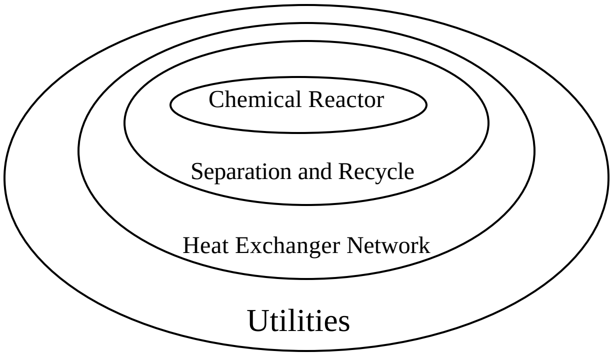


Figure 2: The ‘Onion Skin’ Diagram for Organization of a Chemical Process and Hierarchy of Analysis.

mechanistic models because they are based on conservation laws as well as the physical and chemical attributes of its constituents.

A typical chemical plant includes hundreds of process units such as heat exchangers, reactors, distillation columns, absorption towers and others. The constraints for these units are either based on conservation laws (mass and energy balances) or they are based on some other laws of nature which include models for chemical phase equilibrium, kinetic models etc. Mathematically, the constraints fall into two types: equality constraints and inequality constraints. Equality constraints deal with the exact relationships such as material and energy balances in the model. The inequality constraints recognize the various bounds involved. Examples of inequality constraints are upper limits on the temperature of certain streams or upper limits on the capacity of certain units.

A-2. Classification of Variables and Determination of Parameters

After the constraints are formulated, the variables in the process are divided into two groups, measured variables and unmeasured variables. The measured variables are the variables which are directly measured from the distributed control systems (DCS) and the plant control laboratory. The remaining variables are the unmeasured variables. For redundancy, there must be more measured variables than the degree of freedom.

The parameters in the model can also be divided into two types. The first type of parameters is the constant parameters, which do not change with time. Examples of these are reaction activation energy, heat exchanger areas etc. The other type of parameters is the time-varying parameters such as catalyst deactivation and heat exchanger fouling factors. These are treated as parameters because they change very slowly with time. They are related to the equipment conditions and not the operating conditions.

A-3. Flowsim Interface

Flowsim is used to develop the process model, and it has a graphical user interface with interactive capabilities. Process units are represented as rectangular shapes whereas the process streams are represented as lines with arrows between these units. Each process unit and stream included in the flowsheet must have a name and a description. Process information is divided into the following six categories; equality constraints, inequality constraints, unmeasured variables, measured variables, parameters and constants.

The information in the first five categories is further classified by associating it with either a unit or a stream in the flowsheet. For example, for a unit that is a heat exchanger, the relevant information includes the mass balance and heat transfer equations, limitations on the flowrates and temperatures if any, the heat transfer coefficient parameter and all the intermediate variables defined for that exchanger.

For a stream, the information includes its temperature, pressure, total flowrate, molar flowrates of individual components etc. Also, information not linked to any one unit or stream is called the ‘Global Data’. For example, the overall daily profit of the process is a global unmeasured variable.

The sixth category of constants can be grouped into different sets based on their physical significance. For example, constants related to heat exchangers can be placed in one group and those related to reactors into another group.

Flowsim also has a seventh category of information called as the ‘enthalpy coefficients’. This stores the list of all the chemical components in the process and their enthalpy coefficients for multiple temperature ranges. All of this process information is entered with the help of the interactive, user-customized graphic screens of Flowsim. The formulation of process models and the classification of process information for the contact process is given in section II. The next step of Advanced Process Analysis System is on-line optimization.

B. The Online Optimization Program

Once the process model has been developed using Flowsim, the next step is to conduct on-line optimization. On-line optimization is the use of an automated system which adjusts the operation of a plant based on product scheduling and production control to maximize profit and minimize emissions by providing setpoints to the distributed control system. As shown in Figure 3, it includes three important steps: combined gross error detection and data reconciliation, simultaneous data reconciliation and parameter estimation and plant economic optimization. In combined gross error detection and data reconciliation, a set of accurate plant measurements is generated from plant’s Distributed Control System (DCS). This set of data is used for estimating the parameters in plant models. Parameter estimation is necessary to have the plant model match the current performance of the plant. Then the economic optimization is conducted to optimize the economic model using this current plant model as constraints and this generates the optimal set points for the Distributed Control System.

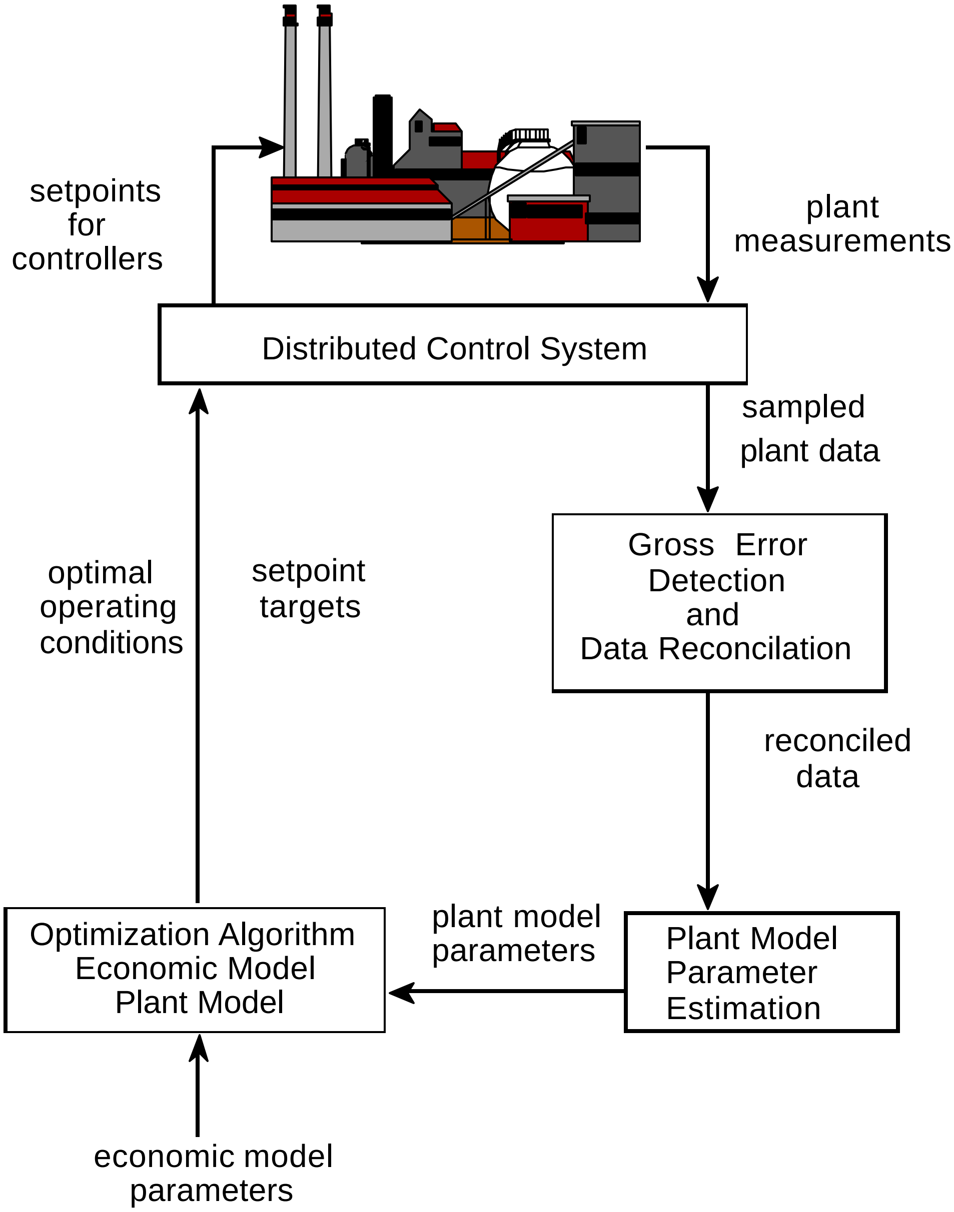


Figure 3: Simplified Structure of Online Optimization

Each of the above three-optimization problems in on-line optimization has a similar mathematical statement as following:

Optimize: *Objective function*
Subject to: *Constraints from plant model.*

where the objective function is a joint distribution function for data validation or parameter estimation and a profit function (economic model) for plant economic optimization. The constraint equations describe the relationship among variables and parameters in the process, and they are material and energy balances, chemical reaction rates, thermodynamic equilibrium relations, and others.

To perform data reconciliation, there has to be more measurements than necessary to be able to rectify errors in instruments. For redundancy, the number of measurements to determine the unmeasured variables is given by the degree of freedom, which is calculated using the following equation.

Degree of freedom = Total number of variables – Total number of equality constraints + Number of chemical reactions

Also, the unmeasured variables have to be determined by the measured variables, called observability. If an unmeasured variable can not be determined by a measured variable, it is unobservable. This is called the 'observability and redundancy criterion', which needs to be satisfied.

B-1. Combined Gross Error Detection and Data Reconciliation

The process data from distributed control system is subject to two types of errors, random error and gross error, and the gross error must be detected and rectified before the data is used to estimate plant parameters. Combined gross error detection and data reconciliation algorithms can be used to detect and rectify the gross errors in measurements for on-line optimization. These algorithms are measurement test method using a normal distribution, Tjoa-Biegler's method using a contaminated Gaussian distribution, and robust statistical method using robust functions. The theoretical performance of these algorithms has been evaluated by Chen, 1998.

Based on Chen's study, the Tjao-Biegler's method is the best for chemical processes and is used to perform combined gross error detection and data reconciliation. When gross errors are in the range of $-\sigma$ to σ, it detects and rectifies gross errors in plant data sampled from distributed control system. This step generates a set of measurements containing only random errors. Then, this set of measurements is used for simultaneous parameter estimation and data reconciliation using the least squares method. This step provides the reconciled data and the updated parameter values in the plant model for economic optimization. Finally, optimal set points are generated for the distributed control system from the economic optimization using the updated plant and economic models. This optimal procedure can be used for any process to conduct on-line optimization.

B-2. Simultaneous Data Reconciliation and Parameter Estimation

The general methodology for this is similar to the methodology of combined gross error detection and data reconciliation. The difference is that the parameters in plant model are considered as variables along with process variables in simultaneous data reconciliation and parameter estimation rather than being constants in data reconciliation. Both process variables and parameters are simultaneously estimated. Based on Chen's study, the least squares algorithm is used to carry out the combined gross error detection and data reconciliation. The data set produced by the parameter estimation is free of any gross errors, and the updated values of parameters represent the current state of the process. These parameter values are now used in the economic optimization step.

B-3. Plant Economic Optimization

The objective of plant economic optimization is to generate a set of optimal operating set points for the distributed control system. This set of optimal set points will maximize the plant profit, satisfy the current constraints in plant model, meet the requirements for the demand of the product and availability of raw materials, and meet the restriction on pollutant emission. This optimization can be achieved by maximizing the economic model (objective function) subject to the process constraints. The objective function can be different depending on the goals of the optimization. The objectives can be to maximize plant profit, optimize plant configuration for energy conservation, minimize undesired by-products, minimize the waste/pollutant emission, or a combination of these objectives. The result of the economic optimization is a set of optimal values for all the measured and unmeasured variables in the process. These are then sent to the distributed control system (DCS) to provide set points for the controllers.

The on-line optimization program of the Advanced Process Analysis System retrieves the process model and the flowsheet diagram from Flowsim. Additional information needed to run online optimization includes plant data and standard deviation for measured variables; initial guess values, bounds and scaling factors for both measured and unmeasured variables; and the economic objective function. The program then constructs the three optimization and uses GAMS (General Algebraic Modeling System) to solve them. Results of all three problems can be viewed using the graphical interface of Flowsim.

The contact process will be used to demonstrate the use and capabilities of the on-line optimization program. This is described in Section VI.

C. The Chemical Reactor Analysis Program

Having optimized the process operating conditions for the most current state of the plant, the next step in the Advanced Process Analysis System is to evaluate modifications to improve the process and reduce emission and energy consumption. First, the chemical reactors in the process are examined. The reactors are the key units of chemical plants. The performance of reactors significantly affects the economic and environmental aspects of the plant operation. The formulation of constraints in these types of units is very important and complicated owing to the various types of reactors and the complex reaction kinetics. Unlike a heat exchanger whose constraints are similar regardless of types of equipment, there is a great variation in deriving the constraints for reactors.

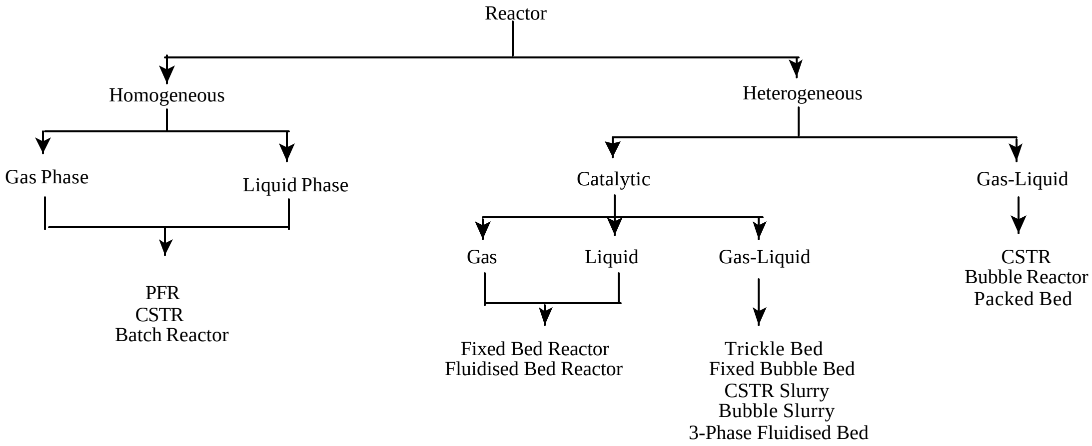


Figure 4: The Reactor Analysis Program Outline

The chemical reactor analysis program of the Advanced Process Analysis System is a comprehensive, interactive computer simulation that can be used for modeling various types of reactors such as Plug Flow, CSTR and Batch reactors. This is shown in Figure 4. Reaction phases included are homogeneous gas, homogeneous liquid, catalytic liquid, gas-liquid etc. The options for energy model include isothermal, adiabatic and non-adiabatic.

The kinetic data needed for the reactor system includes the number of reactions taking place in the reactor and the number of chemical species involved. For each reaction, the stoichiometry and reaction rate expressions also need to be supplied. The physical properties for the chemical species can be retrieved from Flowsim.

The feed stream for the reactor is obtained from Flowsim and its temperature, pressure, flowrate and composition are retrieved using the results from on-line optimization. Finally, the dimensions of the reactor and heat transfer coefficients are supplied. All of this data is used with various types of reactors to predict their performance and select the best one. The reactant concentration, conversion, temperature and pressure are calculated as function of reactor length or space-time. The results can be viewed in both tabular and graphical form.

As the operating process conditions change, the performance of the reactors also can vary to a significant extent. The reactor design program provides a tool to develop an understanding of these relationships. It provides a wide range of different types of reactors, which can be examined and compared to decide the best reactor configuration for economic benefits and waste reduction.

The contact process will be used to demonstrate the use and capabilities of the chemical reactor analysis program. This is described in Section IX.

D. The Heat Exchanger Network Program

The optimization of the chemical reactors is followed by the heat exchanger network optimization as shown in the onion skin diagram in Figure 2. Most chemical processes require the heating and cooling of certain process streams before they enter another process unit or are released into the environment. This heating or cooling requirement can be satisfied by matching of these streams with one another and by supplying external source of heating or cooling. These external sources are called as utilities, and they add to the operating cost of the plant. The Heat Exchanger Network program aims at minimizing the use of these external utilities by increasing energy recovery within the process. It also synthesizes a heat exchanger network that is feasible and has a low investment cost.

There are several ways of carrying out the above optimization problem. Two of the most important ones are the pinch analysis and the mathematical programming methods. Pinch analysis is based on thermodynamic principles whereas the mathematical methods are based on mass and energy balance constraints. The Heat Exchanger Network Program (abbreviated as THEN) is based on the method of pinch analysis (Knopf, 1989).

The first step in implementation of THEN is the identification of all the process streams, which are important for energy integration. These important streams usually include streams entering or leaving heat exchangers, heaters and coolers. The flowsheeting diagram of Flowsim can be an important aid in selection of these streams.

The next step in this optimization task involves retrieval of the necessary information related to these streams. Data necessary to perform heat exchanger network optimization includes the temperature, the flowrate, the film heat transfer coefficient and the enthalpy data. The enthalpy data can be in the form of constant heat capacities for streams with small temperature variations. For streams with large variations, it can be entered as temperature-dependent enthalpy coefficients. The film heat transfer coefficients are needed only to calculate the areas of heat exchangers in the new network proposed by THEN.

The temperature and flowrates of the various process streams are automatically retrieved from the results of online optimization. The set points obtained after the plant economic optimization are used as the source data. The physical properties such as the heat capacities, enthalpy coefficients and film heat transfer coefficients are retrieved from the Flowsim.

The third step in the heat exchanger network optimization is classification of streams into hot streams and cold streams. A hot stream is a stream that needs to be cooled to a lower temperature whereas a cold stream is a stream that needs to be heated to a higher temperature. Usually, streams entering a cooler or the hot side of a heat exchanger are the hot streams whereas streams entering through a heater or the cold side of a heat exchanger are the cold streams. The final step in this problem requires the specification of the minimum approach temperature. This value is usually based on experience.

Having completed all of the above four steps, the heat exchanger network optimization is now performed using THEN. Thermodynamic principles are applied to determine the minimum amount of external supply of hot and cold utilities. The Composite Curves and the Grand Composite Curve are constructed for the process. These curves show the heat flows at various temperature levels. Illustrations of the composite curves are given in Figure 5. A new network of heat exchangers, heaters and coolers is proposed, which features the minimum amount of external utilities. This network drawn in a graphical format is called the Network Grid Diagram. An example of a network grid diagram is given in Figure 6. Detailed information about the network can be viewed using the interactive features of the user interface.

The amount for minimum hot and cold utilities calculated by the Heat Exchanger Network Program is compared with the existing amount of utilities being used in the process. If the existing amounts are greater than the minimum amounts, the process has potential for reduction in operating cost. The network grid diagram synthesized by THEN can be used to construct a heat exchanger network that achieves the target of minimum utilities. The savings in operating costs are compared with the cost of modification of the existing network, and a decision is made about the implementation of the solution proposed by THEN.

The contact process will be used to demonstrate the use and capabilities of the THEN program. This is described in Section VII.

E. The Pollution Index Program

The final step in the Advanced Process Analysis System is the assessment of the pollution impact of the process on the environment. This has become an important issue in the design and optimization of chemical processes because of growing environmental awareness

The pollution assessment module of the Advanced Process Analysis System is called ‘The Pollution Index Program’. It is based on the Waste Reduction Algorithm (Hilaly, 1994) and the Environmental Impact Theory (Cabezas et. al., 1997).

E-1. Waste Reduction Algorithm

The WAR algorithm is based on the generic pollution balance of a process flow diagram.

Pollution Accumulation = Pollution Inputs + Pollution Generation - Pollution Output (I.1)

It defines a quantity called as the 'Pollution Index' to measure the waste generation in the process. This pollution index is defined as:

$$I = \text{wastes/products} = -(G\text{Out} + G\text{Fugitive}) / GP_n \qquad (I.2)$$

This index is used to identify streams and parts of processes to be modified. Also, it allows comparison of pollution production of different processes. The WAR algorithm can be used to minimize waste in the design of new processes as well as modification of existing processes.

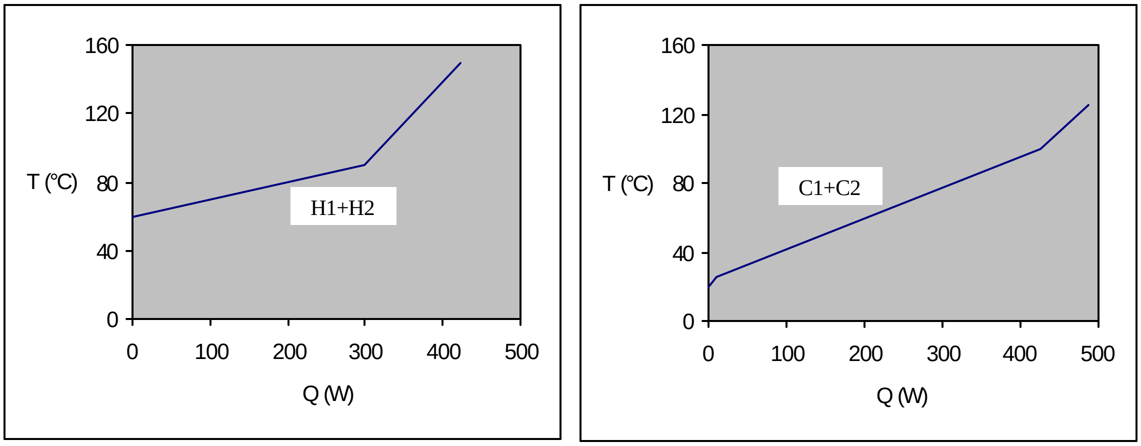


Figure 5: The Composite Curves for Hot Streams (on the left side) and Cold Streams (on the right side) for The Simple Process.

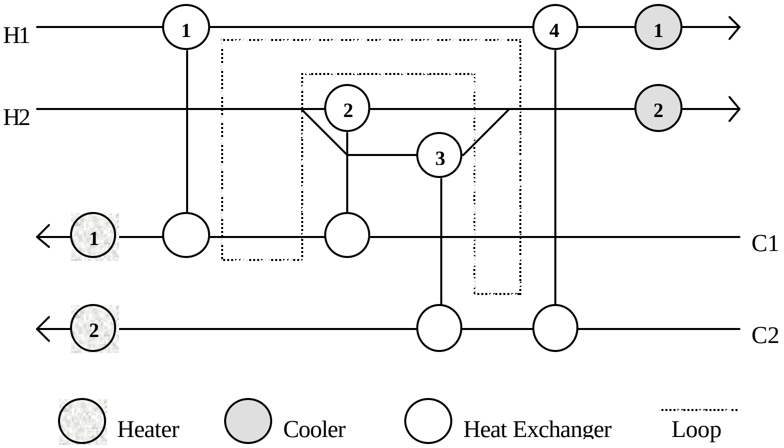


Figure 6: The Grid Diagram

E-2. The Environmental Impact Theory

The Environmental Impact Theory (Cabezas et. al., 1997) is a generalization of the WAR algorithm. It describes the methodology for evaluating potential environmental impacts, and it can be used in the design and modification of chemical processes. The environmental impacts of a chemical process are generally caused by the energy and material that the process takes from and emits to the environment. The potential environmental impact is a conceptual quantity that can not be measured. But it can be calculated from related measurable quantities.

The generic pollution balance equation of the WAR algorithm is now applied to the conservation of the Potential Environmental Impact in a process. The flow of impact $\dot{I}$, in and out of the process is related to mass and energy flows but is not equivalent to them. The conservation equation can be written as

$$\frac{dI_{sys}}{dt} = \dot{I}_{in} - \dot{I}_{out} + \dot{I}_{gen} \tag{I.3}$$

where I_{sys} is the potential environmental impact content inside the process, $\dot{I}_{in}$ is the input rate of impact, $\dot{I}_{out}$ is the output rate of impact and $\dot{I}_{gen}$ is the rate of impact generation inside the process by chemical reactions or other means. At steady state, equation I.3 reduces to

$$0 = \dot{I}_{in} - \dot{I}_{out} + \dot{I}_{gen} \tag{I.4}$$

Application of this equation to chemical processes requires an expression that relates the conceptual impact quantity $\dot{I}$ to measurable quantities. The input rate of impact can be written as

$$\dot{I}_{in} = \sum_j \dot{I}_j = \sum_j \dot{M}_j^{in} \sum_k x_{kj} \Psi_k \tag{I.5}$$

where the subscript 'in' stands for input streams. The sum over j is taken over all the input streams. For each input stream j, a sum is taken over all the chemical species present in that stream. M_j is the mass flow rate of the stream j and the x_{kj} is the mass fraction of chemical k in that stream. Q_k is the characteristic potential impact of chemical k.

The output streams are further divided into two different types: Product and Non-product. All non-product streams are considered as pollutants with positive potential impact and all product streams are considered to have zero potential impact. The output rate of impact can be written as

$$\dot{I}_{out} = \sum_j \dot{I}_j = \sum_j \dot{M}_j^{out} \sum_k x_{kj} \Psi_k \tag{I.6}$$

where the subscript 'out' stands for non-product streams. The sum over j is taken over all the non-product streams. For each stream j, a sum is taken over all the chemical species.

Knowing the input and output rate of impact from the equations I.5 and I.6, the generation rate can be calculated using equation I.4. Equations I.5 and I.6 need values of potential environmental impacts of chemical species. The potential environmental impact of a chemical species (Ψ_k) is calculated using the following expression

$$\Psi_k = \sum_l \; {}_l\Psi^s_{k,l} \tag{I.7}$$

where the sum is taken over the categories of environmental impact. "$_l$ is the relative weighting factor for impact of type l independent of chemical k. Q$^s_{k,l}$ is the potential environmental impact of chemical k for impact of type l. Values of Q$^s_{k,l}$ for a number of chemical species can be obtained from the report on environmental life cycle assessment of products (Heijungs, 1992).

There are nine different categories of impact. These can be subdivided into four physical potential impacts (acidification, greenhouse enhancement, ozone depletion and photochemical oxidant formation), three human toxicity effects (air, water and soil) and two ecotoxicity effects (aquatic and terrestrial). The relative weighting factor "$_l$ allows the above expression for the impact to be customized to specific or local conditions. The suggested procedure is to initially set values of all relative weighting factors to one and then allow the user to vary them according to local needs. More information on impact types and choice of weighting factors can be obtained from the report on environmental life cycle assessment of products (Heijungs, 1992).

To quantitatively describe the pollution impact of a process, the conservation equation is used to define two categories of Impact Indexes. The first category is based on generation of potential impact within the process. These are useful in addressing the questions related to the internal environmental efficiency of the process plant, i.e., the ability of the process to produce desired products while creating a minimum of environmental impact. The second category measures the emission of potential impact by the process. This is a measure of the external environmental efficiency of the process i.e. the ability to produce the desired products while inflicting on the environment a minimum of impact.

Within each of these categories, three types of indexes are defined which can be used for comparison of different processes. In the first category (generation), the three indexes are as follows.

1) $\dot{I}^{NP}_{gen}$ This measures the the total rate at which the process generates potential environmental impact due to nonproducts. This can be calculated by subtracting the input rate of impact ($\dot{I}_{in}$) from the output rate of impact ($\dot{I}_{out}$).

Total rate of Impact generated based on Potential Environmemtal Impact is:

$$\dot{I}^{NP}_{gen} = \dot{I}^{NP}_{out} - \dot{I}^{NP}_{in} \tag{I.8}$$

where $\dot{I}_{in}$ is calculated using equation I.5 and $\dot{I}_{out}$ is calculated using Equation I.6.

2) $\hat{I}_{gen}^{NP}$ This measures the potential impact created by all nonproducts in manufacturing a unit mass of all the products. This can be obtained from dividing $\dot{I}_{gen}^{NP}$ by the rate at which the process outputs products.

Specific Impact generated based on Potential Environmental Impact is:

$$\hat{I}_{gen}^{NP} = \frac{\dot{I}_{gen}^{NP}}{\sum_p \dot{P}_p} = \frac{\dot{I}_{out}^{NP} - \dot{I}_{in}^{NP}}{\sum_p \dot{P}_p} \tag{I.9}$$

where $\sum_p \dot{P}_p$ is the total rate of output of products

3) $\hat{M}_{gen}^{NP}$ This is a measure of the mass efficiency of the process, i.e., the ratio of mass converted to an undesirable form to mass converted to a desirable form. This can be calculated from $\hat{I}_{gen}^{NP}$ by assigning a value of 1 to the potential impacts of all non-products.

Rate of Generation of Pollutants per Unit Product is

$$\hat{M}_{gen}^{NP} = \frac{\sum_j \dot{M}_j^{(out)} \sum_k x_{kj}^{NP} - \sum_j \dot{M}_j^{(in)} \sum_k x_{kj}^{NP}}{\sum_p \dot{P}_p} \tag{I.10}$$

The indexes in the second category (emission) are as follows.

4) $\dot{I}_{out}^{NP}$ This measures the the total rate at which the process outputs potential environmental impact due to nonproducts. This is calculated using equation I.6.

5) $\hat{I}_{out}^{NP}$ This measures the potential impact emitted in manufacturing a unit mass of all the products. This is obtained from dividing $\dot{I}_{out}^{NP}$ by the rate at which the process outputs products.

Specific Impact Emission based on Potential Environmental Impact is:

$$\hat{I}_{out}^{NP} = \frac{\dot{I}_{out}^{NP}}{\sum_p \dot{P}_p} \tag{I.11}$$

6) $\hat{M}_{out}^{NP}$ This is the amount of pollutant mass emitted in manufacturing a unit mass of product. This can be calculated from $\hat{I}_{out}^{NP}$ by assigning a value of 1 to the potential impacts of all non-products.

Rate of Emission of Pollutants per Unit Product is:

$$\hat{M}_{out}^{NP} = \frac{\sum_j \dot{M}_j^{(out)} \sum_k x_{kj}^{NP}}{\sum_p \dot{P}_p} \tag{I.12}$$

Indices 1 and 4 can be used for comparison of different designs on an absolute basis whereas indices 2, 3, 5 and 6 can be used to compare them independent of the plant size. Higher values of indices mean higher pollution impact and suggest that the plant design is inefficient from environmental safety point of view.

E-3. Steps in Using the Pollution Index Program

The first step in performing pollution analysis is the selection of relevant streams. Environmental impact of a chemical process is caused by the streams that the process takes from and emits to the environment. Therefore, only these input and output streams are considered in performing the pollution index analysis. Other streams, which are completely internal to the process, are excluded. In the Pollution Index Program, this selection of input-output streams is automatically done based on the plant information entered in Flowsim.

The next step in the pollution index analysis is the classification of the output streams into product and non-product streams. All streams which are either sold as product or which are used up in a subsequent process in the production facility are considered as product streams. All other output streams, which are released into the environment, are considered as non-product streams. All non-product streams are considered as pollutant streams whereas all product streams are considered to have zero environmental impact.

Pollution index of a stream is a function of its composition. The composition data for the streams is retrieved from the results of on-line optimization performed earlier. This can be either in terms of the molar flowrates or fractions. Additional data such as the specific environmental impact potential values for the chemical species is available in the report on environmental life cycle assessment of products.

The last piece of information required is the relative weighting factors for the process plant. These values depend on the location of the plant and its surrounding conditions. For example, the weighting factor for photochemical oxidation is higher in areas that suffer from smog.

Having finished all of the above prerequisite steps, the pollution index program is now called to perform the analysis. Mass balance constraints are solved for the process streams involved, and the equations of the Environmental Impact Theory are used to calculate the pollution index values. The pollution indices of the six types discussed earlier are reported for the process. Three of these are based on internal environmental efficiency whereas the other three are based on external environmental efficiency. Higher the values of these indices, higher is the environmental impact of the process.

The pollution index program also calculates pollution indices for each of the individual process streams. These values help in identification of the streams that contribute more to the overall pollution impact of the process. Suitable process modifications can be done to reduce the pollutant content of these streams.

Every run of on-line optimization for the process is followed by the pollution index calculations. The new pollution index values are compared with the older values. The comparison shows how the change in process conditions affects the environmental impact. Thus, the pollution index program can be used in continuous on-line monitoring of the process.

The contact process will be used to demonstrate the use and capabilities of the pollution index program. This is described in section VIII.

F. Windows Interface

An important part of the advanced process analysis system is development of the Graphical User Interface (GUI). It was necessary to have a programming language, which could integrate all of above applications into one program. It should also be able to exchange information between these programs without the intervention of the process engineer.

There are four competitive object-oriented, rapid applications development tools with GUI windows that have the above capabilities. These are Microsoft’s Visual Basic, Borland’s Delphi32, IBM’s Visual Age and Powersoft’s Powerbuilder.

We have chosen Visual Basic as the interface development language. It is integrated with Windows 95 and Windows NT, has a low cost and can link applications over a local area network. Also, Visual Basic supports the Object Linking and Embedding technology in OLE2. This feature allows the programs to exchange information regardless of the physical or logical location or data type and format.

Visual Basic 5.0 was used to develop windows interface for Flowsim, the on-line optimization program, the chemical reactor design program, THEN, the heat exchanger network design program, and the pollution index program. As mentioned earlier, sharing of process, economic and environmental data is the key to integration of these programs into one package. Storing the output data of all these programs in different files had many disadvantages. Both storage and retrieval of data would be inefficient. Also, exchange of information between the programs would require reading data from a number of files thus reducing the speed.

As a result, it was decided to use a database to store all of the necessary information to be shared by the component programs as shown in Figure 1. A database is nothing but a collection of information in form of tables. The information in a table is related to a particular subject or purpose. A number of database formats are in use in industry. We have chosen Microsoft Access as the database system for this project.

A table in Microsoft Access consists of rows and columns, which are called *Records* and *Fields* respectively in the database terminology. Each *Field* can store information of a particular kind e.g. a table ‘Stream Data’ can have a field called ‘Temperature’ which stores all the stream temperatures. Another table can have a field called ‘Prices’ which has the prices of all the reactants and products. Each *Record* is a data entry, which fills all the fields of a table. So, the Stream Data table in the above example can have a record for stream S1, which has values for temperatures, pressure, flowrates etc. entered in the respective fields.

Microsoft Access is an interactive database system. Using Access, you can store data in tables according to the subject. This makes tracking of data very efficient. Also, you can specify relationships between different tables. Consequently, it is easy to bring together information related to various topics. Microsoft Access takes full advantage of the graphical power of windows. Also, it is fully compatible with Microsoft’s Visual Basic and Microsoft Excel, which is a significant advantage for this application.

G. Summary

The Advanced Process Analysis System offers a combination of powerful process design and modification tools. The Visual Basic interface integrates all of these into one system and makes the application very user-friendly. The best way to understand the application of the Advanced Process Analysis System is apply it to an actual process. The contact process for sulfuric acid manufacture, (D-train) at IMC Agrico, Convent, Louisiana is used for this purpose. This process incorporates nearly all of the process units found in chemical plant and refineries including packed bed catalytic chemical reactors, absorption towers and heat exchangers among others. The next section gives a detailed description of the IMC Agrico sulfuric acid process.

II. DESCRIPTION OF CONTACT PROCESS FOR SULFURIC ACID

IMC Agrico’s D-train plant is a 4800 TPD 93%(wt) sulfuric acid plant built by Chemical Construction Company in 1966. The overall yield of elemental sulfur to sulfuric acid is 97.5%(wt).

The contact process is a three-step process that produces sulfuric acid and steam from air, molten sulfur and water. The process flow diagram is shown in Figure 7, and the process consists of three sections, which are the feed preparation section, the reactor section, and the absorber section.

In the feed preparation section, molten sulfur feed is combusted with dry air in the sulfur burner. The reaction is:

$$S + O_2 ==> SO_2 + Heat$$

The reaction is exothermic and goes to completion. The gas leaving the burner is composed of sulfur dioxide, nitrogen, and unreacted oxygen at approximately 1800 °F.

The equipment used in this section includes an air filter, drying tower, a blower and a sulfur burner. The blower is five-stage, polytropic steam driven turbine with an efficiency of about 65%. The pump takes in approximately 130,000 cfm of ambient air at -10 inches of water and discharges it at about 170 inches of water and 165 °F under normal operation. The blower turbine speed is adjusted to change the production rate for each train. The drying tower removes ambient moisture from the intake air with 98 wt. % sulfuric acid flowing at a rate of about 4-5000 gpm. The tower is 25 feet in diameter and contains 17 ft 2 inches of packing.

In the sulfur burner, the dry compressed air discharged from the turbine reacts with molten sulfur to produce sulfur dioxide. A cold air bypass is used to maintain the burner exit temperature at 1800 °F. This temperature is setpoint controlled because it is the inlet temperature for the waste heat boiler (WB). The setpoint is dictated by equipment limitations and design considerations.

The sulfur dioxide, along with nitrogen and unreacted oxygen enters the waste heat boiler. The waste heat boiler is equipped with a hot gas bypass so that the temperature of the gases entering the first catalyst bed can be controlled at 800 °F. This boiler is a shell and tube type supplied with water from the steam drum. The boiler produces saturated steam at about 500 °F and 670 psig and utilizes about 10% blowdown.

The second section of the contact process plant is the reactor section. The reactor consists of four beds packed with two different types of vanadium pentoxide catalyst. The first two beds are packed with Monsanto’s type LP-120 catalyst whereas the third and forth beds are packed with type LP-110. The purpose of using two different catalysts is to have higher catalyst activity in the low temperature zones of the third and fourth beds.

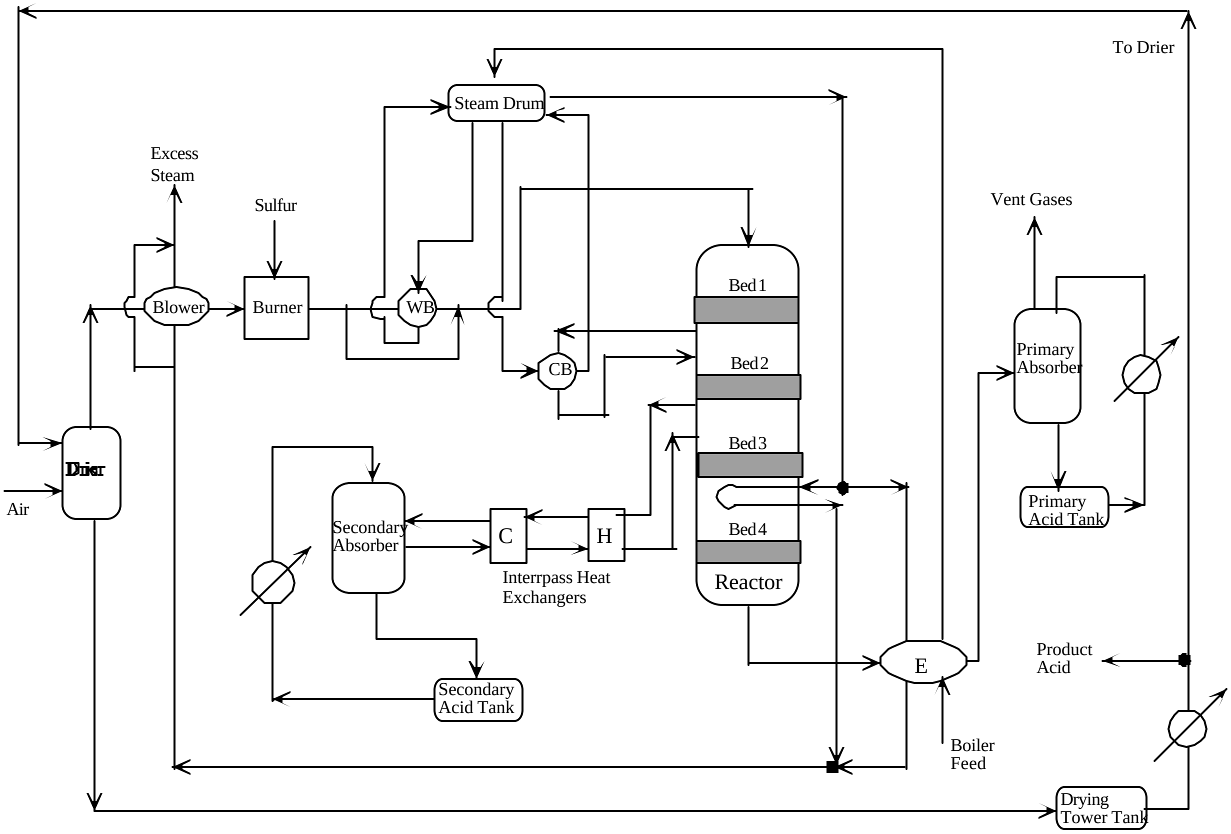


Figure 7 The Process Flow Diagram for D-Train Sulfuric Acid Plant

In the reactor section, the gas mixture from the feed preparation section is further reacted in the fixed catalyst beds to produce sulfur trioxide and heat according to the reaction:

$$2SO_2 + O_2 \implies 2SO_3 + \text{Heat}$$

The reaction is exothermic and the equilibrium conversion decreases with the increase in reaction temperature. For this reason, the process uses four packed beds, and heat exchangers between each bed remove the produced energy to reduce the temperature.

As shown in Figure 8, the equilibrium conversion of sulfur dioxide decreases with the increase in operating temperature. Removing reaction heat from each reactor increases the conversion of sulfur dioxide to sulfur trioxide and this removed heat is used to produce steam. Also, the equilibrium conversion increases by decreasing the concentration of sulfur trioxide and an inter-pass tower is used to absorb and remove sulfur trioxide from the gas stream between the second and the third catalyst beds. This design ensures higher conversion in the reactor beds.

As shown in Figure 7, the exit gases from the first bed are cooled in the converter boiler (CB). This boiler has the same configuration as the waste heat boiler. It is supplied with water from the steam drum. It produces saturated steam at 500 °F and 670 psig and utilizes about 10%

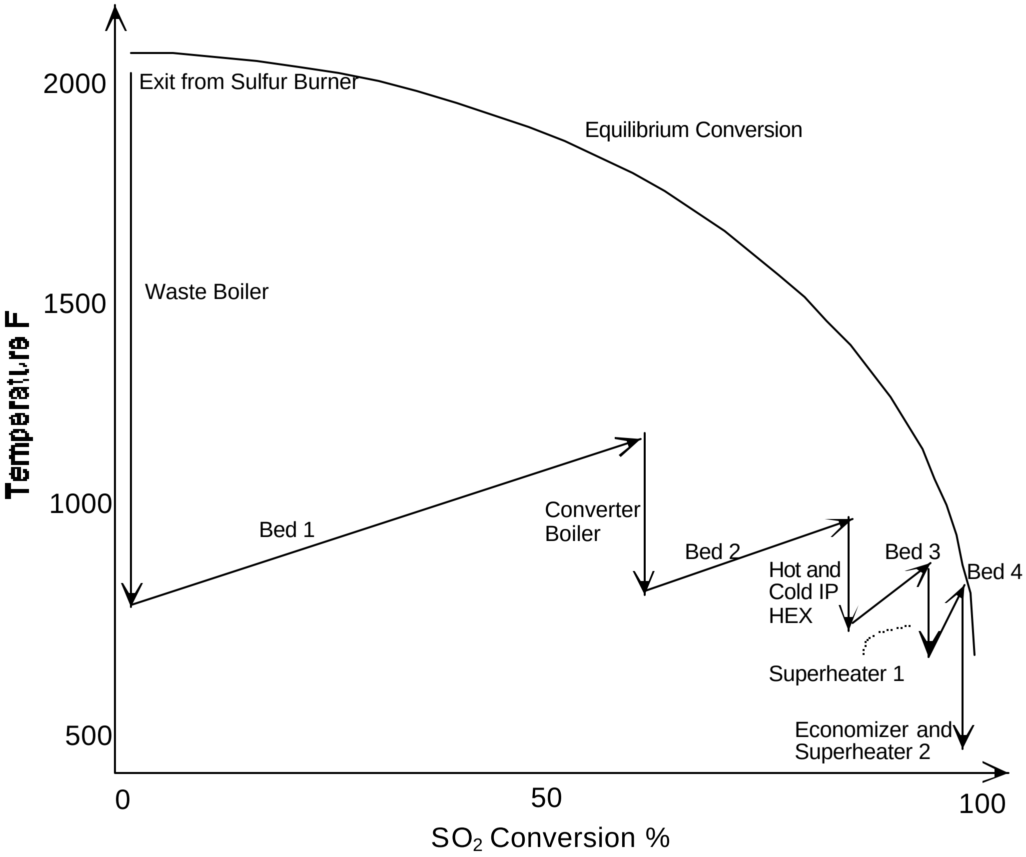


Figure 8 Temperature-Conversion of SO2 Plot for D-train Sulfuric Acid Process

blowdown. The hot and cold inter-pass heat exchangers (H and C) are used to cool the gases from the second catalyst bed before these gases are passed to the inter-pass tower. The gases from the third catalyst bed are cooled by superheater-1, which is a finned tube heat exchanger. This super heater produces superheated steam from the saturated steam produced by the boilers. The gases from the fourth bed consist of sulfur trioxide, nitrogen, oxygen and a small amount of sulfur dioxide. They are first cooled by superheater-2 followed by the economizer (E). In the superheater-2, cooling is done by the saturated steam coming from the steam drum whereas in the economizer, it is done by the boiler feed water. The cooled gases are then passed to the final tower for absorption of sulfur trioxide.

The final section of the contact process plant is the absorber section. In this section the SO_3 is absorbed from the reaction gas mixture into 98%(wt) sulfuric acid to produce a more concentrated acid. Also, heat is produced according to the equation:

$$SO_3 + H_2O \Rightarrow H_2SO_4 + \text{Heat}$$

As shown in Figure 7, the equipment in this section includes the final acid absorption tower, an inter-pass absorption tower, two acid absorption tanks and a drying tower acid tank. The two absorption towers use 98%(wt) acid to produce more concentrated acid. Water is added to the tanks to keep the sulfuric acid strength at 93 %(wt) in drying tower acid tank and 98%(wt) in absorption tower tanks. The 93%(wt) acid from the drying tower acid tank is sold as the product acid. The exit gases from the final absorption tower containing unreacted air and small amount of sulfur dioxide are discharged to the air.

The boiler feed water is pre-heated to 380 °F at 740 psig by the economizer and is then sent to the steam drum. It then passes to the waste heat boiler and the converter boiler to produce saturated steam at 675 psig. This saturated steam is circulated back to the steam drum. It then goes to superheater-1 and superheater-2 to generate superheated steam at 626 psig. The superheated steam is used to drive the turbine and the excess steam is one of the products, which is used in an adjacent plant.

This concludes the description of the D-train sulfuric acid process. The next section explains the development of the process model.

III. PROCESS MODEL FOR SULFURIC ACID PROCESS

A process model of a chemical engineering process is a set of constraint equations, which represents a mathematical model of relationships between the various plant units and process streams. Before the constraint equations are formulated, it is important to note that in order to have an accurate model of the process, it is essential to include the key process units such as reactors, heat exchangers and absorbers. These units affect the economic and pollution performance of the process to a significant extent. Certain other units are not so important and can be excluded from the model without compromising the accuracy. For the contact process, the four converters, sulfur burner, boilers, superheaters, acid absorbers were identified as the important units to be included in the model whereas the acid tanks, acid coolers, air blower, air filter etc. were excluded from the model. The complete list of the process units and process streams included in the model is given in Tables 1 and 2. The process model diagram with these units and streams is shown in Figure 9.

Having selected the process units and streams, the next step is to develop the constraint equations. The constraint equations are entered in Flowsim using the format of the GAMS language. They become the process model which is used to reconcile plant measurements, estimate parameters, optimize the profit and minimize emissions from the plant. The constraint formulation techniques are very similar for process units of the same type. Therefore, this section is divided into four sub-sections; heat exchanger network, reactors, absorption towers and overall balance for the plant. Each of these sub-sections explains how constraints (material and energy balances) are written for that particular type of unit. For each type, detailed constraint equations are shown for a representative unit.

Table 1 Process Units in the IMC Agrico Sulfuric Acid Process Model (Refer to Figure 9, the Process Model Diagram)

Name of Unit	**Description**
Burner	Sulfur Burner
Cboiler	Converter Boiler
ColdIP	Cold Interpass Heat Exchanger
Converter1	Reactor Bed 1
Converter2	Reactor Bed 2
Converter3	Reactor Bed 3
Converter4	Reactor Bed 4
Drum	Steam Drum
Economizer	Economizer
Finalab	Secondary Acid Absorber
Furnspl	Splitter after the burner
HotIP	Hot Interpass Heat Exchanger
Interab	Primary Acid Absorber
MixRec	Mixer after the waste heat boiler
Mixsteam	Steam Mixer before the drum
Sh1	Superheater1
Sh2	Superheater2
Splsteam	Steam Splitter after the drum
Splwater	Water Splitter after the economizer
Wboiler	Waste Heat Boiler

Table 2 Process Streams in the IMC Agrico Sulfuric Acid Process Model (Refer to Figure 9, the Process Model Diagram)

Name of Stream	Description
s06	Inlet Air Stream
s07	Sulfur Burner Outlet Gas Stream
s08	Gas stream entering the waste heat boiler
s08a	Waste Heat Boiler Bypass
s09	Waste Heat Boiler Outlet
s10	Converter 1 Inlet
s11	Converter 1 Outlet
s12	Converter 2 Inlet
s13	Converter 2 Outlet
s14	Hot gases entering Cold IP exchanger
s15	Gas stream entering secondary absorber
s16	Gas stream leaving secondary absorber
s19	Cold gases entering Hot IP exchanger
s20	Converter 3 Inlet
s21	Converter 3 Outlet
s22	Converter 4 Inlet
s23	Converter 4 Outlet
s235	Gas stream entering economizer
s24	Gas stream leaving economizer
s25	Stack gas stream
s50	Sulfur Stream
sbd	Blowdown stream from the drum
sbfw	Boiler Feed Water
shp1	Superheated steam from superheater1
shp2	Superheated steam from superheater2
ss1	Saturated steam entering the drum
ss1a	Saturated steam from the waste heat boiler
ss1b	Saturated steam from the converter boiler
ss2	Saturated steam leaving the drum
ss4	Saturated steam entering superheater1
ss5	Saturated steam entering superheater1
sw1	Water leaving the economizer
sw1a	Water entering the waste heat boiler
sw1b	Water entering the converter boiler

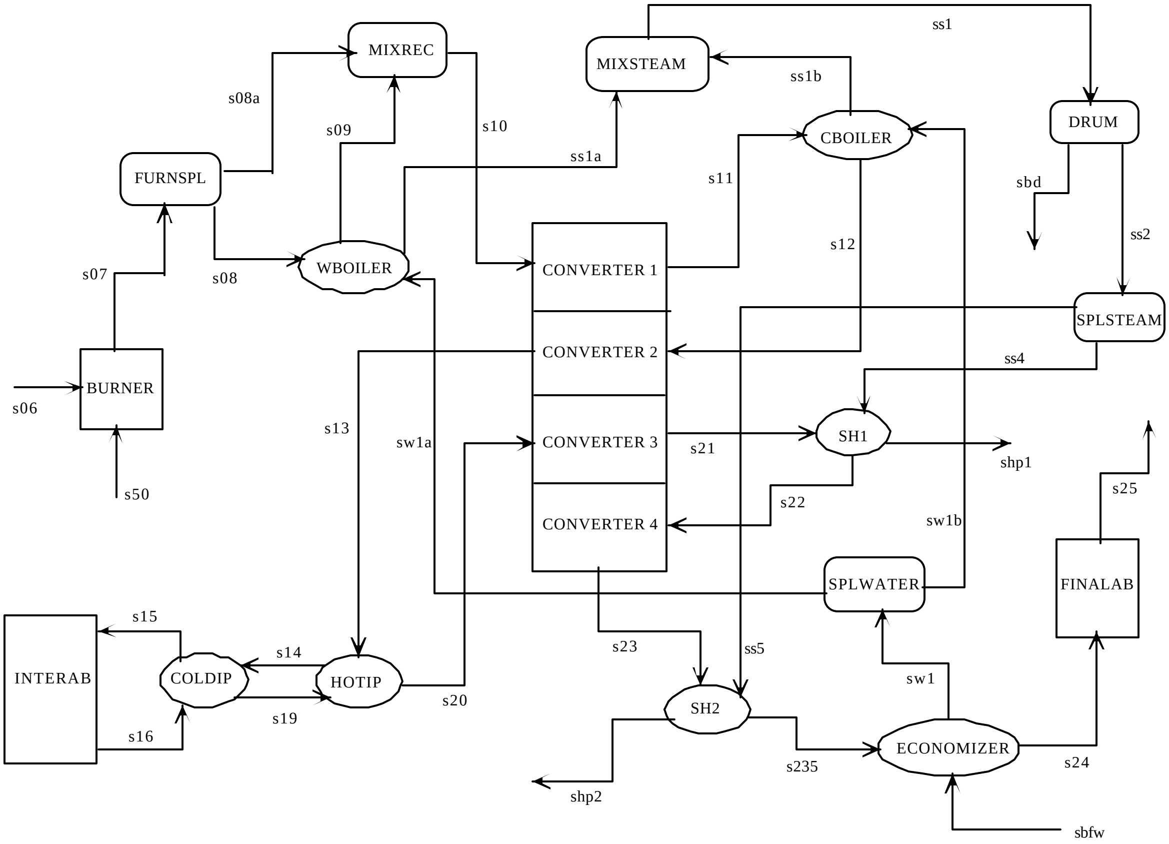


Figure 9 The Process Model Diagram for D-Train Sulfuric Acid Plant

A. Heat Exchanger Network

As shown in Figure 9, the heat exchanger network in sulfuric acid plant includes two boilers, two gas-to-gas hot and cold inter-pass heat exchangers, two superheaters and a gas-to-compressed-water economizer. In these units, there is no mass transfer or chemical reaction. The inlet component flowrates are equal to the outlet component flow rates for both sides. The energy balance states that the decrease of the enthalpy (MJ/s) in the hot side is equal to the increase of enthalpy in cold side plus the heat loss, i.e.,

$$(H^{inlet} - H^{outlet})_{hot} = (H^{outlet} - H^{inlet})_{cold} + Q_{loss}. \qquad \text{(III.1)}$$

For the hot inter-pass heat exchanger (HotIP), s13 is the inlet stream on the cold side whereas s14 is the outlet stream on the hot side. s19 is the inlet stream on the cold side and s20 is the outlet stream on cold side. The energy balance can be written as

$$(H^{inlet} - H^{outlet})_{hot} = \Sigma F_{13}^{(i)} h_{13}^{(i)} - \Sigma F_{14}^{(i)} h_{14}^{(i)} \quad \text{and} \qquad \text{(III.2)}$$

$$(H^{inlet} - H^{outlet})_{cold} = \Sigma F_{19}^{(i)} h_{19}^{(i)} - \Sigma F_{20}^{(i)} h_{20}^{(i)}$$

where $F_{13}^{(i)}$ is the molar flowrate (kmol/s) of species i in stream s13 and $h_{13}^{(i)}$ is the enthalpy (MJ/kmol) of species i in stream s13. The total molar flowrate of stream s13 and the total enthalpy of stream s13 are given by the equations

$$F_{13} = \Sigma F_{13}^{(i)} \text{ and} \qquad \text{(III.3)}$$
$$H_{13} = \Sigma F_{13}^{(i)} h_{13}^{(i)}$$

where the summation is done over all the species i present in stream s13. This naming convention is used for all the flowrates and enthalpies. The number in the subscript of the variable can be used to identify the stream to which it belongs. $H^{inlet}{}_{hot}$ is the enthalpy of the inlet stream on hot side, and it has units of MJ/s.

The heat transferred in an exchanger is proportional to heat transfer area A, overall heat transfer coefficient U, and the logarithm mean temperature difference between the two sides ΔT_{lm}, i.e., $Q = UA \; \Delta T_{lm}$, where Q is the enthalpy change on cold side, i.e.,

$$Q = (H^{inlet} - H^{outlet})_{cold} = \Sigma F_{19}^{(i)} h_{19}^{(i)} - \Sigma F_{20}^{(i)} h_{20}^{(i)} \qquad \text{(III.4)}$$

The material and energy balances as well as heat transfer equations are similar for all units in heat exchanger network. Table 3 gives the constraint equations for the hot inter-pass heat exchanger as an example of process constraint equations for all heat exchanger units.

The first two rows of the Table 3 under material balance give the overall mass balance and all of the species mass balances. The overall mass balance is the summation of all species mass balances. Therefore, if all of the species mass balances are used to describe the process, then the overall mass balance does not need to be included since it is redundant. The species mass balances are used to describe the relationship of the input and output flow rate variables.

In the constraints of Table 3, F denotes the component molar flow rate, kmol/sec, and its superscript i and subscript k denote the component names and stream numbers respectively. h's in the equations represent the species enthalpies of streams (MJ/kmol), and Q_{loss} is the heat loss from the exchanger (MJ/kmol). T is the stream temperature (K), and ΔT_{lm} is the logarithm mean temperature difference (K) between hot and cold sides of the exchanger. In the heat transfer equation, U and A are the overall heat transfer coefficient and heat transfer area respectively.

The two rows in Table 3 under energy balances give the overall energy balance and heat transfer equation. In addition, the enthalpy for each species, h(T), expressed as a polynomial function of the stream temperature is also given in the table. The enthalpy equations for gases, compressed water, and superheated steam are developed in Appendix A.

In these equations, the total flow rates, species flow rates (or composition), and temperatures of streams are the measurable variables. Species enthalpies and the mean temperature difference are also measurable variables because they can be calculated from other measurable variables such as temperatures and flowrates. The heat transfer coefficients are the process parameters to be estimated. The heat transfer area, heat loss and coefficients in enthalpy equations are constants. The heat loss from the exchanger is estimated to be 2% of the amount of heat exchanged. The equations for the other heat exchangers are shown in Appendix A.

B. Reactor System

The reactor system in this plant includes a sulfur burner and four catalytic converters. The following describes the constraint equations for sulfur burner and the first converter.

Table 3 The Constraint Equations for Hot Inter-Pass Heat Exchanger

Material Balances	
Overall	$(F_{14}^{(SO_3)}+F_{14}^{(SO_2)}+F_{14}^{(O_2)}+F_{14}^{(N_2)})-(F_{13}^{(SO_3)}+F_{13}^{(SO_2)}+F_{13}^{(O_2)}+F_{13}^{(N_2)})=0$ $(F_{20}^{(SO_3)}+F_{20}^{(SO_2)}+F_{20}^{(O_2)}+F_{20}^{(N_2)})-(F_{19}^{(SO_3)}+F_{19}^{(SO_2)}+F_{19}^{(O_2)}+F_{19}^{(N_2)})=0$
Species	$O_2:\quad F_{14}^{(O_2)}-F_{13}^{(O_2)}=0,\qquad F_{20}^{(O_2)}-F_{19}^{(O_2)}=0$ $N_2:\quad F_{14}^{(N_2)}-F_{13}^{(N_2)}=0,\qquad F_{20}^{(N_2)}-F_{19}^{(N_2)}=0$ $SO_2:\quad F_{14}^{(SO_2)}-F_{13}^{(SO_2)}=0,\qquad F_{20}^{(SO_2)}-F_{19}^{(SO_2)}=0$ $SO_3:\quad F_{14}^{(SO_3)}-F_{13}^{(SO_3)}=0,\qquad F_{20}^{(SO_3)}-F_{19}^{(SO_3)}=0$
Energy Balances	
Overall	$\left(\sum_i F_{14}^{(i)}h_{14}^{(i)}-\sum_i F_{13}^{(i)}h_{13}^{(i)}\right)-\left(\sum_i F_{19}^{(i)}h_{19}^{(i)}-\sum_i F_{20}^{(i)}h_{20}^{(i)}\right)+Q_{loss}=0$ where $h^i_k(T)=R(a_1^iT+\frac{1}{2}a_2^iT^2+\frac{1}{3}a_3^iT^3+\frac{1}{4}a_4^iT^4+\frac{1}{5}a_5^iT^5+b_1^i-H_{298}^i)$ $i=SO_2,SO_3,O_2,N_2;\ k=13,14,19,20$
Heat Transfer	$\left(\sum_i F_{20}^{(i)}h_{20}^{(i)}-\sum_i F_{19}^{(i)}h_{19}^{(i)}\right)-\left(U_{ex66}A_{ex66}\right)T_{lm}=0$

When a chemical reaction is involved in the process, it is convenient to use the mole balance to describe relationship of input and output flow rates of a unit for a component. Also, the overall mole balance is obtained from the component mole balances, i.e., the summation of component mole balance gives the overall mole balance. The sulfuric acid process involves three reactions, i.e., reaction of sulfur to sulfur dioxide, reaction of sulfur dioxide to sulfur trioxide, and absorption reaction of sulfur trioxide to sulfuric acid. Mole balances are used to describe the material balances of the units in the process, i.e., all material balance equations for the sulfuric acid process are written with mole balance relations. Moles are conserved when there is no reaction, and the change in the number of moles for a component is determined by the reaction rate and stoichiometric coefficients when there are reactions.

As shown in Figure 9, the inputs of sulfur burner are dry air stream (S06) from main compressor, and liquid sulfur stream (S50). The dry air reacts with molten sulfur to produce sulfur dioxide and heat in the burner. The sulfur dioxide, along with nitrogen and unreacted oxygen enters the waste heat boiler. At the design operating temperature of the sulfur burner, all of the sulfur is converted to sulfur dioxide, and some sulfur trioxide is formed from sulfur dioxide. The plant measurements have shown that 2 % (mol) of the SO_2 is converted into SO_3 in this unit, and this value is incorporated in the mass and energy balances of this unit.

The mole and energy balance equations for the sulfur burner are given in Table 4. The two rows of this table under mole balance give the overall mole balance and component mole balances. The mole balance for each component is established based on the conservation law. The steady state mole balance for a component is written as:

$$F_{in}(i) - F_{out}(i) + F_{gen}(i) = 0 \qquad \text{(III.5)}$$

where i represents the names of components. For the sulfur burner, $F_{in}(i)$, $F_{out}(i)$, and $F_{gen}(i)$ are input air flow rate F06(i), output flow rate F07(i), and generation rates of components from reaction, r(i). The overall mole balance is the summation of all component mole balance equations.

Two reactions take place in this unit, i.e., reaction one of sulfur to sulfur dioxide and reaction two of sulfur dioxide to sulfur trioxide. The entire sulfur is completely converted to sulfur dioxide, and 2% (mole) of the produced sulfur dioxide is further converted to sulfur trioxide in this unit. Therefore, the reaction (generation) rate for each component is related to the input flow rate of sulfur F_{50} and the stoichiometric coefficient of a component in the reaction. Also, the reaction rate of a product component has a positive value and the reaction rate of a reactant component has a negative value. For example, the component mole balance for sulfur dioxide is:

$$SO_2: \quad F_{06}^{SO2} - F_{07}^{SO2} + 0.98 * F_{50} = 0 \qquad \text{(III.6)}$$

where F_{06}^{SO2} and F_{07}^{SO2} are the input and output flow rates of sulfur dioxide, and $0.98*F_{50}$ is the generation rate of sulfur dioxide. For reaction one (complete conversion of sulfur to sulfur dioxide), sulfur dioxide is a product with stoichiometric coefficient of one. In reaction two, sulfur dioxide is a reactant with stoichiometric coefficient of one. Therefore, the total reaction rate for sulfur dioxide in the two reactions is

$$F_{50} - 0.02*F_{50} = 0.98*F_{50}. \qquad \text{(III.7)}$$

Table 4 The Process Constraint Equations for Sulfur Burner

Mole Balances	
Overall	$F_{06} - F_{07} - 0.01F_{50} = 0$ $where\ F_{06} = F_{06}^{O2} + F_{06}^{N2}$ $F_{07} = F_{07}^{O2} + F_{07}^{N2} + F_{07}^{SO2} + F_{07}^{SO3}$
Species	$O_2: \quad F_{06}^{(O_2)} - F_{07}^{(O_2)} - 1.01F_{50} = 0$ $N_2: \quad F_{06}^{(N_2)} - F_{07}^{(N_2)} = 0$ $SO_2: \quad F_{06}^{(SO_2)} - F_{07}^{(SO_2)} + 0.98F_{50} = 0$ $SO_3: \quad F_{06}^{(SO_3)} - F_{07}^{(SO_3)} + 0.02F_{50} = 0$ $S: \quad F_{50} - F_{07}^{(S)} - F_{07}^{(SO2)} - F_{07}^{(SO3)} = 0$ $where \quad F_{06}^{(SO_2)} = 0,\ F_{06}^{(SO_3)} = 0,\ F_{07}^{(S)} = 0$
Energy Balances	
Overall	$F_{50}h^{(sulfur)} + \sum_i F_{06}^{(i)}h_{06}^{(i)} + F_{50}\,\Delta h_{rxn}^{SO_2} + 0.02F_{50}\,\Delta h_{rxn}^{SO_3} - \sum_i F_{07}^{(i)}h_{07}^{(i)} - Q_{loss} = 0$ $where$ $\Delta h_{rxn}^{SO_2} = h(T)^{S} + h(T)^{O_2} - h(T)^{SO_2},$ $\Delta h_{rxn}^{SO_3} = 1.827\times(-24{,}097 - 0.26T + 1.69\times10^{-3}T^2 + 1.5\times10^5/T),\ BTU/lb-mol$
Enthalpy Function	$h^i_k(T) = R(a_1^iT + \frac{1}{2}a_2^iT^2 + \frac{1}{3}a_3^iT^3 + \frac{1}{4}a_4^iT^4 + \frac{1}{5}a_5^iT^5 + b_1^i - H_{298}^i) \quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2, sulfur(L);\ k = 06, 07$

The steady state overall energy balance is established based on the first law of thermodynamics. Neglecting changes in kinetic and potential energy, this equation is (Felder and Rousseau, 1986):

$$-)H + Q - W = 0 \qquad \text{(III.8)}$$

where $)H$ is the change in enthalpy between input and output streams, i.e.,

$)H = H_{out} - H_{in}$ and

$$\Delta H = \sum_{output} F^{(i)} h^{(i)} - \sum_{input} F^{(i)} h^{(i)} + \frac{n_{AR}}{v_A} \Delta h^0{}_{rxn} \qquad \text{(III.9)}$$

Here n_{AR} is the number of moles of reactant A that is reacted, v_A is the stoichiometric coefficient of reactant A in the reaction and $\Delta h^0{}_{rxn}$ is the standard heat of reaction. Here, the reference conditions are that the reactant and product species are at 298°K and 1.0 atmosphere as described in Appendix B. Q is the heat added to the system and W is the amount of work done by the system. The energy equation for sulfur burner unit is written as:

$$F_{50}\, h^{sulfur} + \Sigma\, F_{06}{}^{(i)}\, h_{06}{}^{(i)} + F_{50}\ )h^{SO2}{}_{rxn} + 0.02{*}F_{50}\ )h^{SO3}{}_{rxn} - \Sigma\, F_{07}{}^{(i)}\, h_{07}{}^{(i)} - Q_{loss} = 0 \qquad \text{(III.10)}$$

where the first and second terms represent the energy for input streams S50 and S06. The third and fourth terms in this equation denote the generated rates of heat for reaction one and two. The fifth and sixth terms are the energy for output stream S07 and heat loss from this unit.

In Table 4, F denotes stream species flow rate, kmol/sec, and h represents species enthalpy, MJ/kmol. $)h_{rxn}{}^{SO2}$ and $)h_{rxn}{}^{SO3}$ are the heats of reaction of sulfur oxidation and SO_2 oxidation at the temperature of the burner. Q_{loss} in energy equation denotes the heat loss from sulfur burner. The heat of reaction for sulfur oxidation is calculated from the enthalpies of components at reaction temperature:

$$)h_{rxn}SO_2 = h(T)_S + h(T)_{O2} - h(T)_{SO2} \qquad \text{(III.11)}$$

where the enthalpies are calculated by the regression equations from NASA Technical Manual 4513C (McBride et al., 1993). The detail enthalpy regression functions for all components are given in Appendix A. The enthalpy function used in Equation III.11 is slightly different from enthalpy functions for determining the sensible heat. In the process model, all enthalpy functions for gas streams use sensible enthalpy function except the enthalpy function in Eq. III.11. The reference state for sensible enthalpy function is 298.15 K and 1Bar for species or elements, and enthalpies for O_2, N_2, SO_2, SO_3 at the reference state (298.15 K and 1 Bar) is zero. In equation III.11, the enthalpy functions are not subtracted by the enthalpies of the species or elements at 298.15 K. Therefore, the enthalpy for species (e.g., SO_2) at reference state is the heat of formation for the species, and the enthalpy for elements (e.g., O_2, S) at reference state is zero. The heat of reaction for sulfur dioxide oxidation to sulfur trioxide is calculated from an empirical formula, a function of reaction temperature, which is given in the kinetic model section of Appendix A.

The four catalytic reactors are adiabatic, plug flow reactors. In these converters, sulfur dioxide is converted to sulfur trioxide in an exothermic chemical reaction. The kinetic model for this catalytic reaction was given by Harris and Norman (1972). Harris and Norman developed an empirical function to determine the intrinsic rate for the oxidation reaction of sulfur dioxide. The intrinsic reaction rate equation is given in Figure 10.

The real reaction rate of SO_2 (r_{SO3}) is calculated from the intrinsic rate by multiplying by the reaction effectiveness factor E_f, i.e., $r_{SO3} = r_{SO2}E_f$. This reaction effectiveness factor is a lump parameter that combines all of the mismatches in the kinetic model, and this includes current bulk density and current activity of the catalyst, variation of real wet surface of catalyst. Also, the heat of SO_2 oxidation reaction is determined from an empirical function discussed in Appendix B (Harris and Norman, 1972), which is given with the function (Eq. B-6) to determine the temperature difference between bulk gas and catalyst pellet.

The empirical function for heat of SO_2 oxidation reaction is:

$$)h_{rxn}SO_3 = 1.827\times(-24{,}097-0.26T+1.69\times10\text{-}3T2+1.5\times105/T),\ \text{Btu/lb-mole} \qquad \text{(III.12)}$$

The four reactors are assumed to be perfect plug flow reactors. Therefore, the material and energy balance equations are differential equations for these four packed bed reactors, and they are established based on the conservation laws. The following gives a discussion on the formulation of constraint equations for Converter I, and the material and energy balance equations for this reactor are given in Table 5.

In Figure 9, the input to Converter I is the gas (S10) from the waste heat boiler and the output (S11) goes to converter boiler. In Table 5, the two rows under material balances give overall and species material balances. The two rows under energy balances give the overall energy balance and the enthalpy function for each species. In these equations, r^I_{so2} and r^I_{so3} are the intrinsic reaction rate and the actual reaction rate for Converter I. The intrinsic reaction rate, r^I_{so2}, is determined by an empirical equation given in Figure 10, and the actual reaction rate of SO_2 oxidation, r^I_{so3}, is the product of intrinsic reaction rate and the reaction effectiveness factor E_f^I for Converter I. In Table 5, D^I_B is the bulk density of catalyst in lb/ft^3, and A is the cross section area of converters. $)h_{rxn}^{SO3}$ is the heat of the reaction, and it is determined by an empirical function of temperature given in Equation III.12. F_I and H_I are the molar flow rate in kmol/sec and enthalpy in MJ/sec for Converter I. Also, the boundary conditions for these differential equations are required to connect the variables in these equations to the variables in the input and output streams. These boundary conditions are given with the equations as shown in Table 5.

In the constraint equations for this unit, total flow rates, composition (or species flow rates), and temperatures are measurable variables. The reaction rates and species enthalpies are unmeasurable variables. E_f^I is the process parameter to be estimated. The others, such as cross section area of converter, bulk density of catalyst, and coefficients in enthalpy equations are constants. The equations for the other converters are shown in Section XII.

$$\mathit{Reaction}: \qquad SO_2 + \frac{1}{2}O_2 \rightarrow SO_3$$

SO_2 *conversion rate equation* (*instrinstic reaction rate*):

$$r_{SO_2} = \frac{P^0_{SO_2}\, P^{0\ 1/2}_{O_2}}{(A + BP^{0\ 1/2}_{O_2} + CP^0_{SO_2} + DP_{SO_3})^2}\left[1 - \frac{P_{SO_3}}{K_p P_{SO_2} P_{O_2}^{\ 1/2}}\right]$$

$$r_{SO_2} = \mathit{rate\ of\ reaction},\ \frac{lb\ mole\ of\ SO_2\ converted}{hr - lb\ catalyst}$$

$$P_{O_2}, P_{SO_2}, P_{SO_3} = \mathit{interfacial\ partial\ pressures\ of}\ O_2, SO_2, SO_3, atm$$

$$P^0_{O_2}, P^0_{SO_2} = \mathit{interfacial\ partial\ pressures\ of}\ O_2\ \mathit{and}\ SO_2\ \mathit{at\ zero\ conversion\ under\ the\ total\ pressure\ at\ the\ point\ in\ the\ reator},\ atm$$

$$K_p = \mathit{thermodynamic\ equilibrium\ constant}, atm^{-\frac{1}{2}}$$

$$Log_{10}K_P = 5129/T - 4.869, \qquad T\ in\ {}^oK$$

A, B, C, D *are function of temperature* T:

Catalyst Type $LP-110$:

$$A = e^{-6.80+4960/T},\quad B = 0,\quad C = e^{10.32-7350/T},\quad D = e^{-7.38+6370/T}$$

Catalyst Type $LP-120$:

$$A = e^{-5.69+4060/T},\quad B = 0,\quad C = e^{6.45-4610/T},\quad D = e^{-8.59+7020/T}$$

Figure 10 Rate Equation for the Catalytic Oxidation of SO_2 to SO_3 Using Type LP-110 and LP-120 Vanadium Pentoxide Catalyst

Table 5 The Process Constraint Equations for Converter I

Material Balances	
Overall	$\frac{dF_I}{dL} = -\frac{1}{2} r_{SO_3} A$ $F_I = F10, \text{ at } L = 0; \quad F_I = F11, \text{ at } L = l_I$ $\text{where } r_{SO_3} = r^I_{SO_2} E_f^I \rho_B^I; \; F_I = \sum_i F_I^{(i)}$ $F_I = F_I^{SO2} + F_I^{SO3} + F_I^{O2} + F_I^{N2}$
Species	$SO_3\!: \; \frac{dF_I^{(SO_3)}}{dL} = r_{SO_3} A$ $SO_2\!: \; \frac{dF_I^{(SO_2)}}{dL} = -r_{SO_3} A$ $O_2\!: \; \frac{dF_I^{(O_2)}}{dL} = -\frac{1}{2} r_{SO_3} A$ $N_2\!: \quad F_{11}^{(N_2)} - F_{10}^{(N_2)} = 0$ $B.\,C.\!: \; F_I^{(i)} = F10^{(i)}, \text{ at } L = 0;$ $F_I^{(i)} = F11^{(i)}, \text{ at } L = l_I$ $\text{where } \; i = SO_3, SO_2, O_2$
Energy Balances	
Overall	$\frac{dH_I}{dL} = r_{SO_3} \Delta h_{rxn}^{SO_3} A$ $H_I = H10, \text{ at } L = 0; \; H_I = H11, \text{ at } L = l_I$ $\text{where } H_I = \sum_i F_I^{(i)} h_I^{(i)}$
Enthalpy Function	$h^i_I(T) = R\left(a_1^i T + \frac{1}{2} a_2^i T^2 + \frac{1}{3} a_3^i T^3 + \frac{1}{4} a_4^i T^4 + \frac{1}{5} a_5^i T^5 + b_1^i - H_{298}^i\right) \quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2$

The ordinary differential equations for material and energy balances in this unit are discretized into the algebraic difference equations using improved Euler's method (Carnahan, et al., 1969). These algebraic difference equations are written in GAMS program and solved with the other constraints in the plant model. The boundary conditions of the algebraic difference equations are the input and output conditions of the packed beds.

C. Absorption Tower Section

This section includes an inter-pass absorption tower and a final absorption tower. These units involve mass transfer of SO_3 from gas phase to liquid phase, i.e., the absorption reaction of sulfur trioxide. For both towers, it is assumed that SO_3 in gas stream is completely absorbed by sulfuric acid solution, and all other gases are considered as inert gases. Also, the total molar flow rate for sulfuric acid stream is counted as the sum of molar flow rates of SO_3 and water in the acid stream. Based on these assumptions, the mole flow rate of water in acid stream should remain unchanged between input and output at the absorption tower. The difference between output and input for both SO_3 and total molar flow rates in acid stream is equal to the molar flow rate of SO_3 in gas stream. In Table 6, the material balance equations for interpass absorption tower and final absorption tower are given where SO_3 is completely absorbed from the gas stream S20 and S24 respectively.

The material balance equations in Table 6 are only written for the gas streams. They do not include the sulfuric acid streams because they are excluded from the process model. This was necessary because there are very few measurements available for the acid streams. Also, the rates of absorption of SO_3 in the absorption towers are sufficient to calculate the sulfuric acid product flowrate, which means that exclusion of acid streams does not affect the accuracy of the plant model.

In Table 6, the first two rows give the total and component mole balances for the Interpass absorption tower whereas the next two rows give the same information for final absorption tower. The gas stream leaving the final absorber, S25 is the stack gas stream. The last row in the table relates the component flowrates in the absorber with the stack gas concentrations of SO_2 and O_2.

D. Overall Material Balance

The overall material balance relates the flow rates of raw materials to the production of products and wastes. For the sulfuric acid process, the production rate of sulfuric acid, f_{prod} can be determined by the SO_3 absorption rates in inter-pass and final towers.

$$(F_{15,SO3} + F_{24,SO3}) / F_{prod} = X_{prod} \qquad \text{(III.13)}$$

where X_{prod} is the molar fraction of SO_3 in the acid product stream. The unit of all the flowrates (F_{prod}, $F_{15,SO3}$, $F_{24,SO3}$) is kmol/sec.

Table 6 The Process Constraint Equations for the Interpass Absorption Tower and Final Absorption Tower

Material Balances for Interpass Absorption Tower	
Overall	$F_{15} - F_{15}^{(SO_3)} = F_{16}$
Species	$O_2: \quad F_{16}^{(O_2)} - F_{15}^{(O_2)} = 0$ $N_2: \quad F_{16}^{(N_2)} - F_{15}^{(N_2)} = 0$ $SO_2: \quad F_{16}^{(SO_2)} - F_{15}^{(SO_2)} = 0$ $SO_3: \quad F_{16}^{(SO_3)} = 0$
Material Balances for Final Absorption Tower	
Overall	$F_{24} - F_{24}^{(SO_3)} = F_{25}$
Species	$O_2: \quad F_{25}^{(O_2)} - F_{24}^{(O_2)} = 0$ $N_2: \quad F_{25}^{(N_2)} - F_{24}^{(N_2)} = 0$ $SO_2: \quad F_{25}^{(SO_2)} - F_{24}^{(SO_2)} = 0$ $SO_3: \quad F_{25}^{(SO_3)} = 0$
Stack Gas	$F_{25} C_{O_2} = F_{25}^{(O_2)}$ $F_{25} C_{SO_2} = F_{25}^{(SO_2)}$

The dilution water is used for both the inter-pass and final acid tower dilution tanks. It is used to adjust the acid strength. The amount of dilution water flow rate, F_{dw} (kmol/sec) is determined by the production rate of sulfuric acid (F_{prod}) and the product concentration (X_{prod}), i.e.,

$$F_{dw} = F_{prod}*(1-X_{prod}) \qquad \text{(III.14)}$$

The constraint for the ratio of oxygen to nitrogen in the air is:

$$F_{06,O2} / F_{06,N2} = 0.21 / 0.79 \qquad \text{(III.15)}$$

The average molecular weight of the sulfuric acid product stream can be calculated as

$$\text{mwprod} = X_{prod}*\text{mw\_SO}_3 + (1-X_{prod})*\text{mw\_H}_2\text{O} \qquad \text{(III.16)}$$

where mw_SO_3 and $\text{mw\_H}_2\text{O}$ are molecular weights of SO_3 and H_2O respectively. The SO_2 emission from the plant, which is defined as the pounds of SO_2 released to the environment per ton of acid produced is calculated as

$$\text{emiss} = (F_{25,so2}*64.0*2.204)/(F_{prod}*(\ X_{prod}*\text{mw\_SO}_3+(1-X_{prod})*\text{mw\_H}_2\text{O})\ /1000) \qquad \text{(III.17)}$$

The factor of 1000 converts kgs of acid flowrate to tons whereas the factor of 2.204 converts SO_2 flowrate from kgs to pounds.

The constraint equations for all of the process are given in Appendix A. Having understood the methodology of Advanced Process Analysis System and the sulfuric acid process model, we are now ready to use the Advanced Process Analysis System program. The following section gives detailed instructions on using the program with the contact process.

IV. GETTING STARTED WITH THE ADVANCED PROCESS ANALYSIS SYSTEM

Upon running the Advanced Process Analysis System, the first window presented to the user is the ‘Advanced Process Analysis Desk’. This is shown in Figure 10.

By default, the Advanced Process Analysis System opens a new model named ‘untitled.ioo’ in the program directory. The complete filename for this new model is shown in the bottom left corner of the window. The bottom right corner shows the date and the time the program was started. The file menu provides various options such as opening a new or an existing model. This is shown in Figure 11. The ‘Recent Models’ item in the file menu maintains a list of last four recently used models for easy access.

The Advanced Process Analysis Desk has five buttons leading to the five component programs, which were described in earlier sections. All of these can also be called using the process menu at the top. This is shown in Figure 12.

When a new model is opened, only the ‘Flowsheet Simulation’ button is available. This is because the development of the process model using Flowsim is the first step in the implementation of the Advanced Process Analysis System. Until the flowsheet simulation part is completed, buttons for the other four programs remain dimmed and unavailable.

To implement the Advanced Process Analysis System for the sulfuric acid process described in earlier section, the first step is to develop the process model using the Flowsim program. The ‘Flowsheet Simulation’ button should be now clicked to open the Flowsim program.

V. USING FLOWSIM

Upon clicking the ‘Flowsheet Simulation’ button in Figure 13, the Flowsim window is displayed with the ‘General Information’ box. In the space for model name, let us enter ‘Contact’. In the process description box, let us enter ‘D-train sulfuric acid plant from IMC Agrico Company’. The ‘General Information’ box with this information is shown in Figure 13.

On clicking the ‘OK’ button, the main screen of ‘Flowsim’ is displayed. This is the screen where the user draws the flowsheet diagram. The ‘Model’ menu shown in Figure 14 provides the various commands used to draw the flowsheet diagram. The menu commands are divided into two groups. The first group has commands for drawing the flowsheet diagram whereas the second group has commands for entering various kinds of process information.

The ‘Add Unit’ command should be used to draw a process unit. The ‘Add Stream’ command should be used to draw a process stream between two process units. The program requires that every stream be drawn between two units. However, the input and output streams of a process only have one unit associated with them. To solve this problem, the Flowsim program provides an additional type of unit called ‘Environment I/O’. This can be drawn using the command ‘Add Environment I/O’ in Figure 14. The ‘Lock’ option makes the diagram read-only and does not allow any changes. The diagram can be unlocked by clicking on the command again.

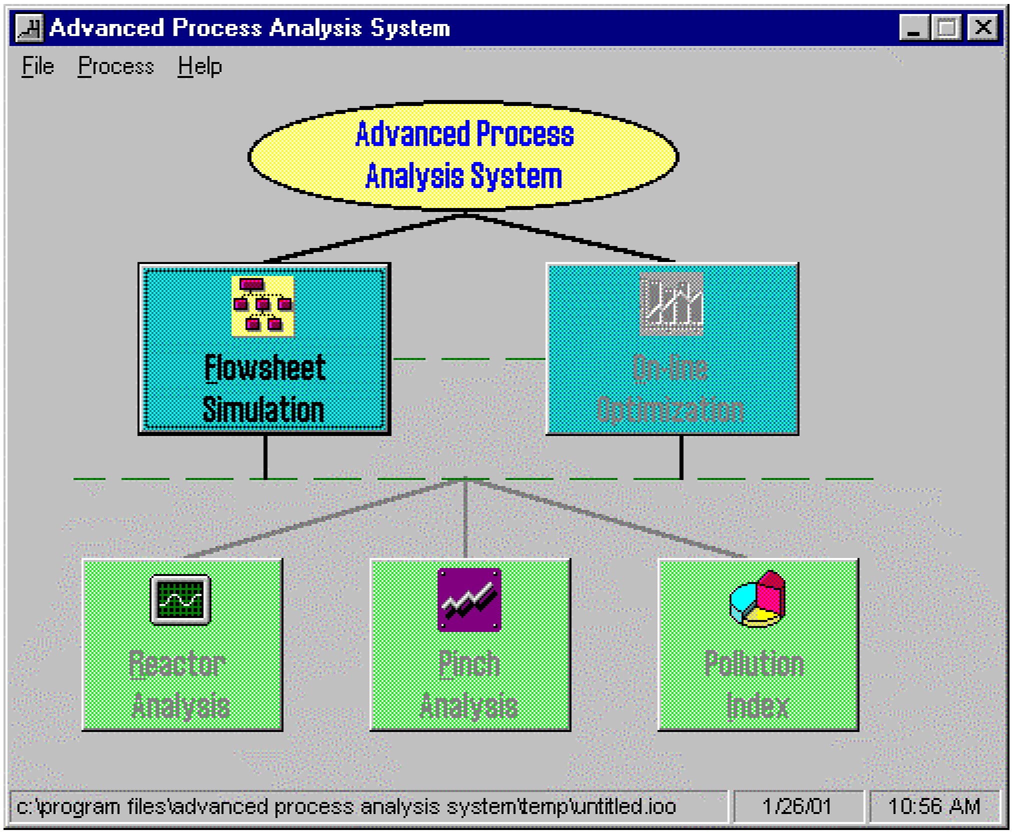


Figure 10 Advanced Process Analysis Desk

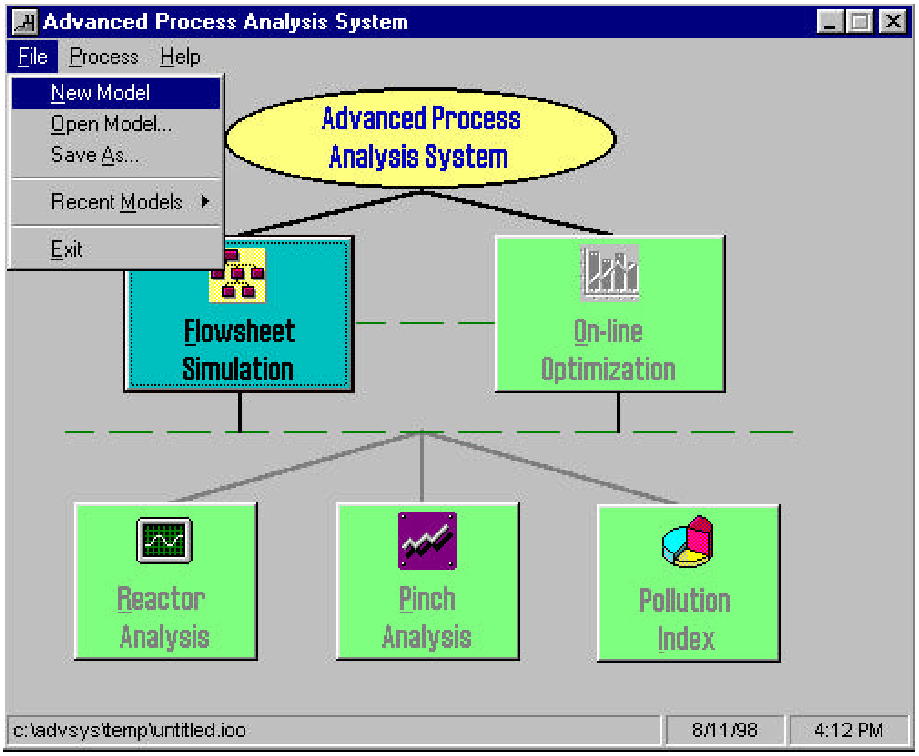


Figure 11 The File Menu of the Advanced Process Analysis Desk

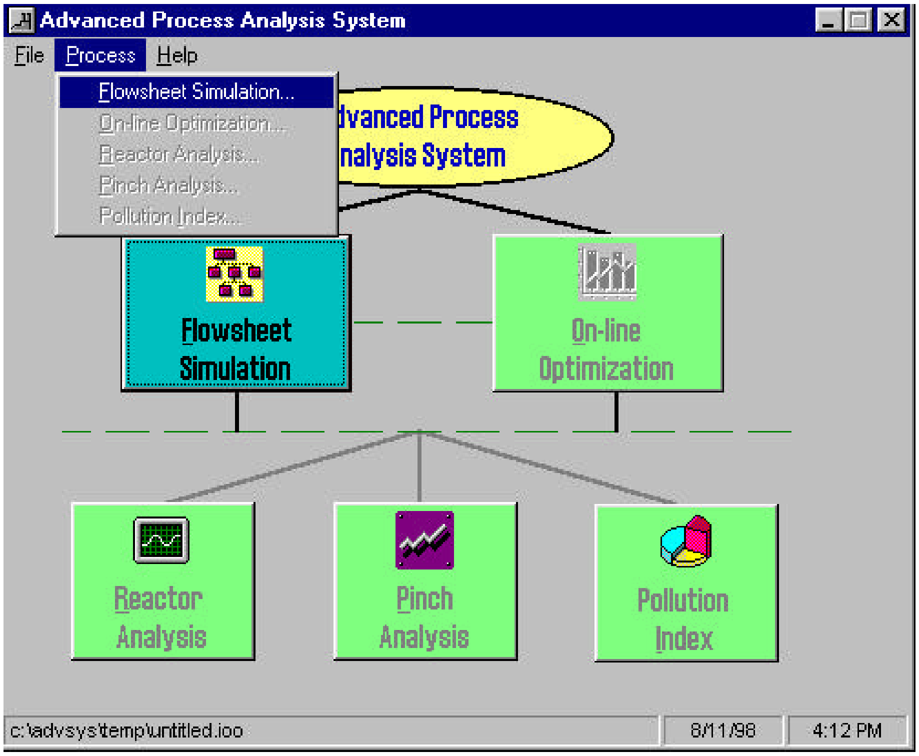
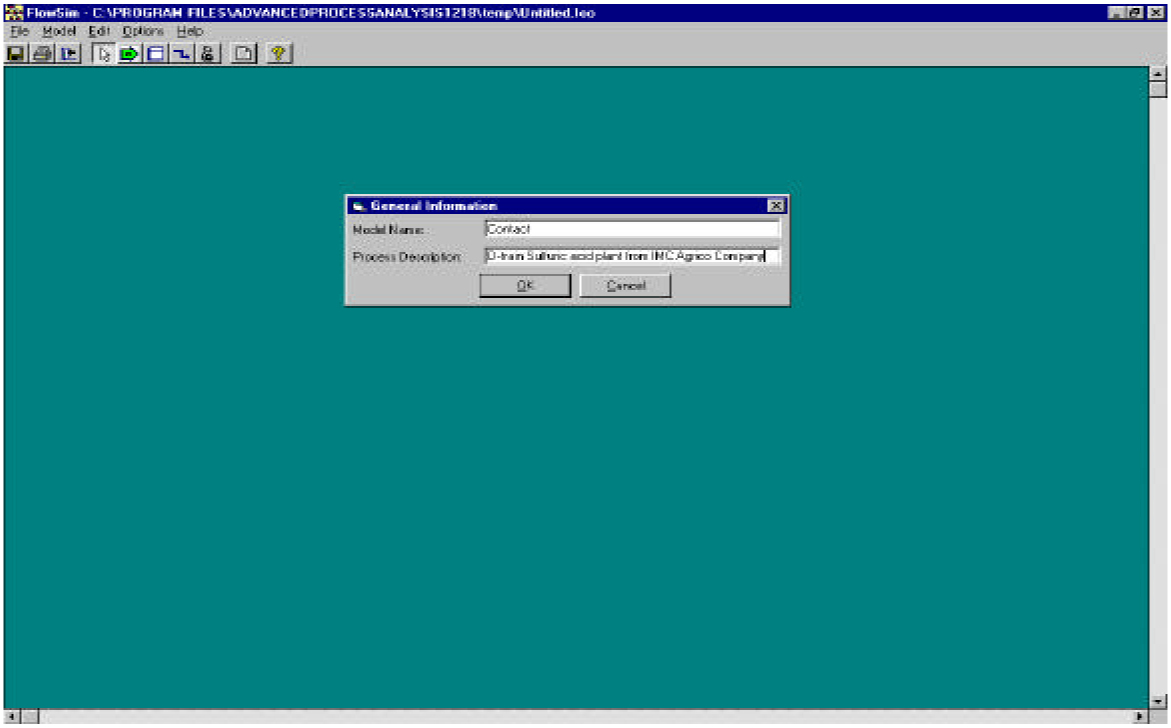


Figure 12 The Process Menu of the Advanced Process Analysis Desk



Model Name: Contact

Process Description: D-train Sulfuric acid plant from IMC Agrico Company

Figure 13 General Information Box

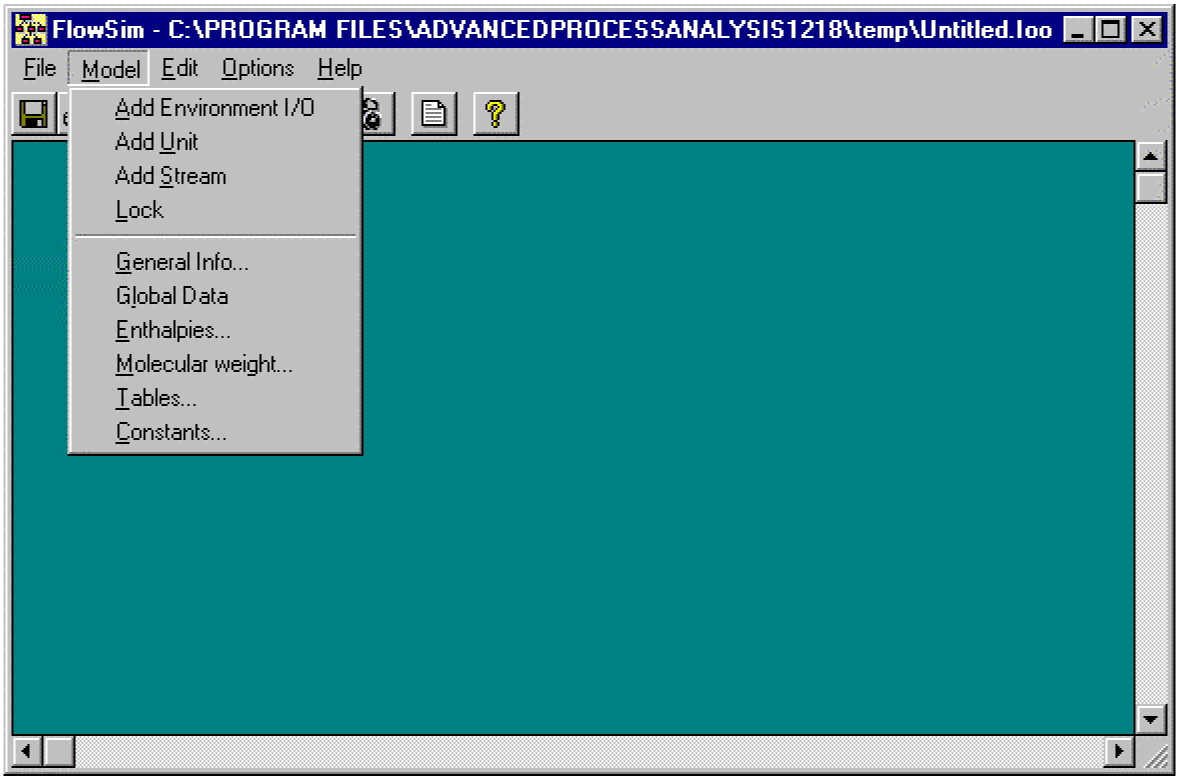
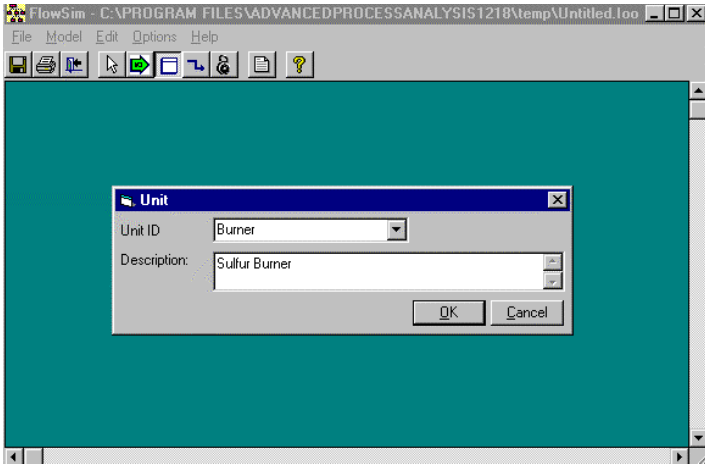


Figure 14 The Model Menu



Unit ID: Burner

Description: Sulfur Burner

Figure 15 The Unit Window

Now, let us use these commands to draw the flowsheet diagram for the IMC Agrico sulfuric acid process. Although Flowsim allows the units and streams to be drawn in any order, it is recommended that while drawing a process model, one should start with the feed and then add units and streams in order. Let us draw the sulfur burner, which is the unit with air and sulfur input. Select the 'Add Unit' command from the 'Model' menu. The mouse cursor changes to a hand. The cursor can now be dragged to draw a rectangle.

Once, the mouse button is released, a small input window appears on the screen as shown in Figure 15. For every process unit that is drawn in Flowsim, the user is required to enter a unique Unit ID and description. For the sulfur burner, let us enter 'Burner' as the unit ID and 'Sulfur Burner' as the description.

Now, let us draw the waste heat boiler in the flowsheet diagram. Let us enter the Unit ID 'Wboiler' and description 'Waste heat boiler'. With these two units, the screen looks like in Figure 16.

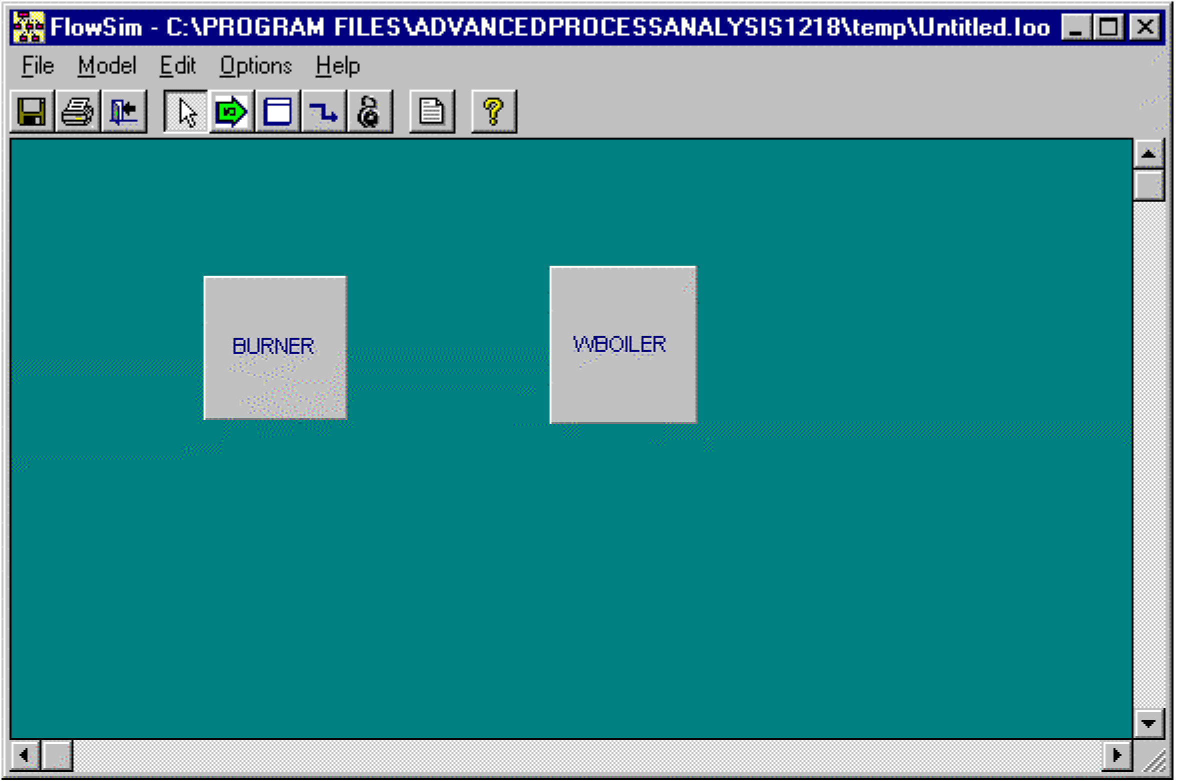
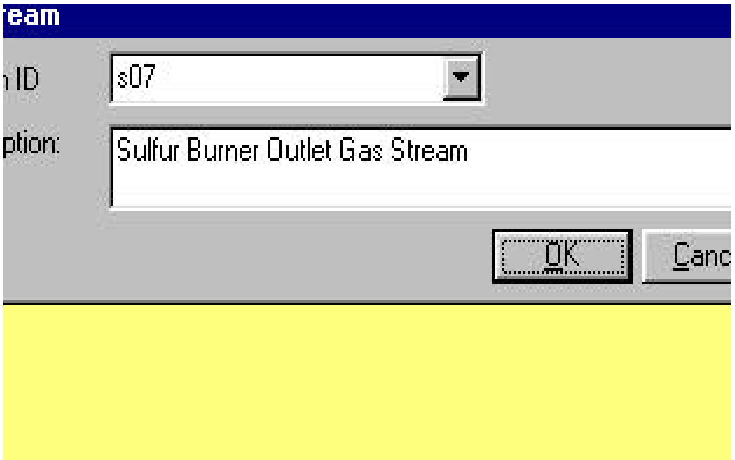


Figure 16   Flowsheet Screen with two Units

.



ID s07

ption: Sulfur Burner Outlet Gas Stream

Figure 17 The Stream Window

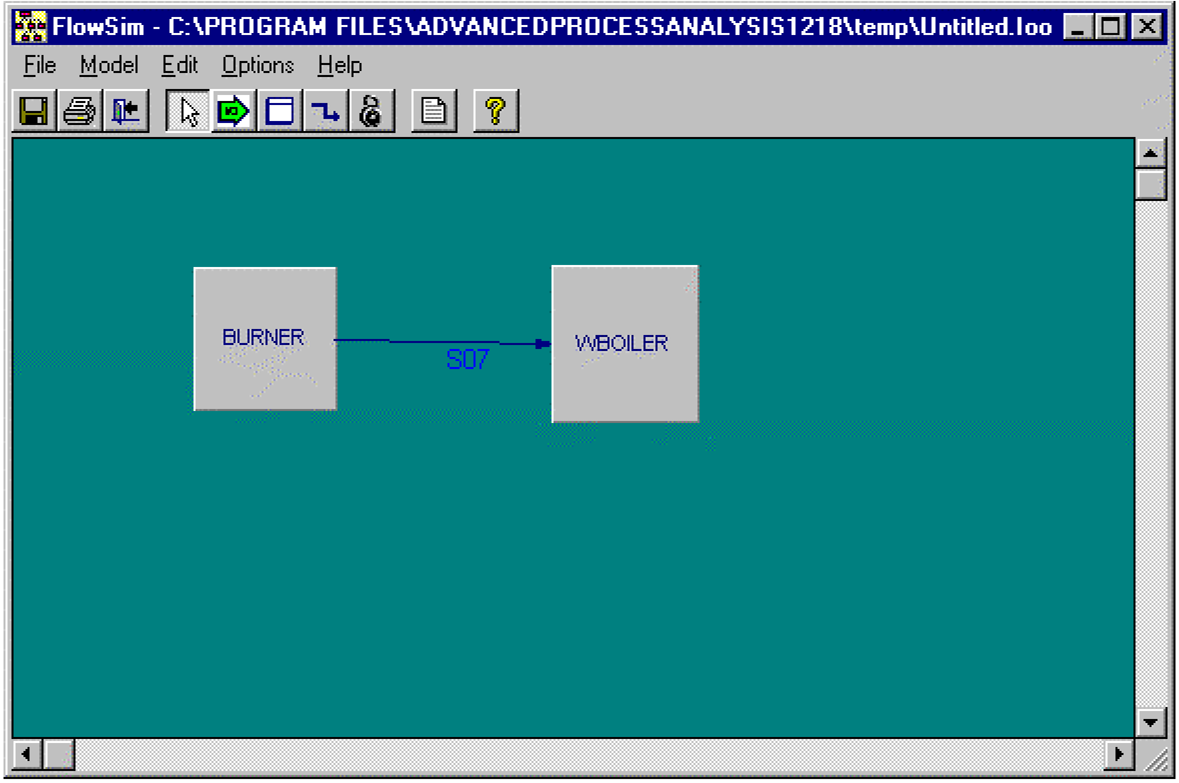


Figure 18 Flowsim Screen with two Units and a Stream

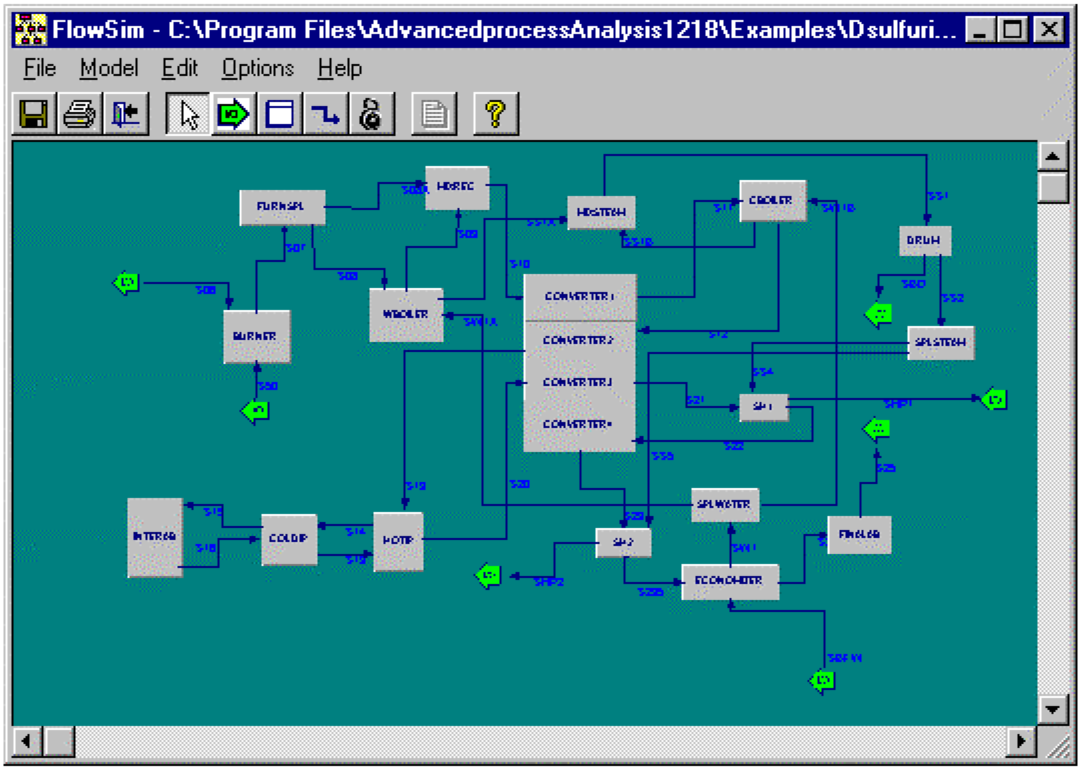


Figure 19 The Flowsim Screen with the Complete Process Diagram for Sulfuric Acid Process Model

Now, let us add the stream that leaves the sulfur burner and enters the waste heat boiler. To do this, select the ‘Add stream’ command from the ‘Model’ menu. The cursor changes to a small circle. Position the cursor on the Burner unit and drag the cursor to the Wboiler unit. The program now displays a small box shown in Figure 17. Let us enter the stream ID ‘s07’ and the description ‘Sulfur Burner Outlet Gas Stream’

With the Burner, Wboiler and s07 stream, the Flowsim screen looks as shown in Figure 18. In this way, the entire process flow diagram for the sulfuric acid process can be drawn using the Model menu commands. After drawing the complete diagram, the Flowsim screen looks as shown in Figure 19.

The ‘Edit’ menu at the top of the Flowsim screen provides various options for editing the diagram. It is shown in Figure 20. To use the Edit commands, a unit in the flowsheet diagram has to be selected first by clicking on it. The cut, copy and paste commands can be used for both units as well as streams. The ‘Delete’ command can be used to permanently remove a unit or a stream from the diagram. The ‘Rename’ command can be used to change the unit ID for a unit or to change the stream ID for a stream. The ‘Properties’ command can be used to change the appearance of a unit or a stream.

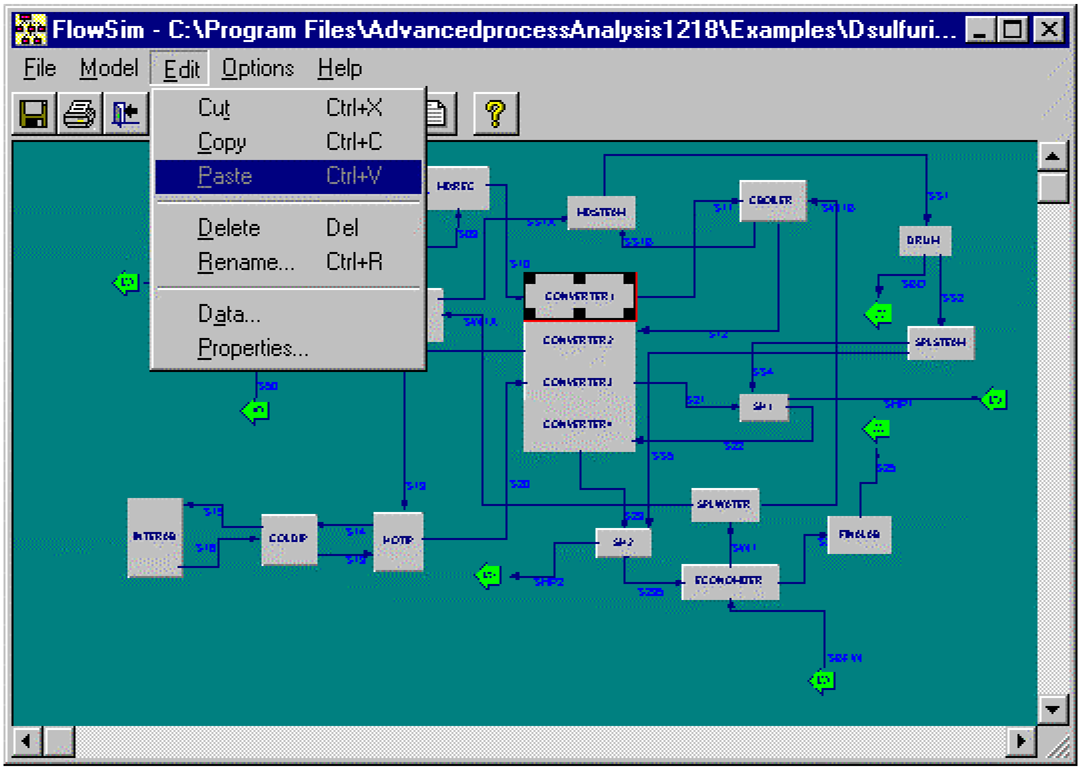


Figure 20 The Edit Menu

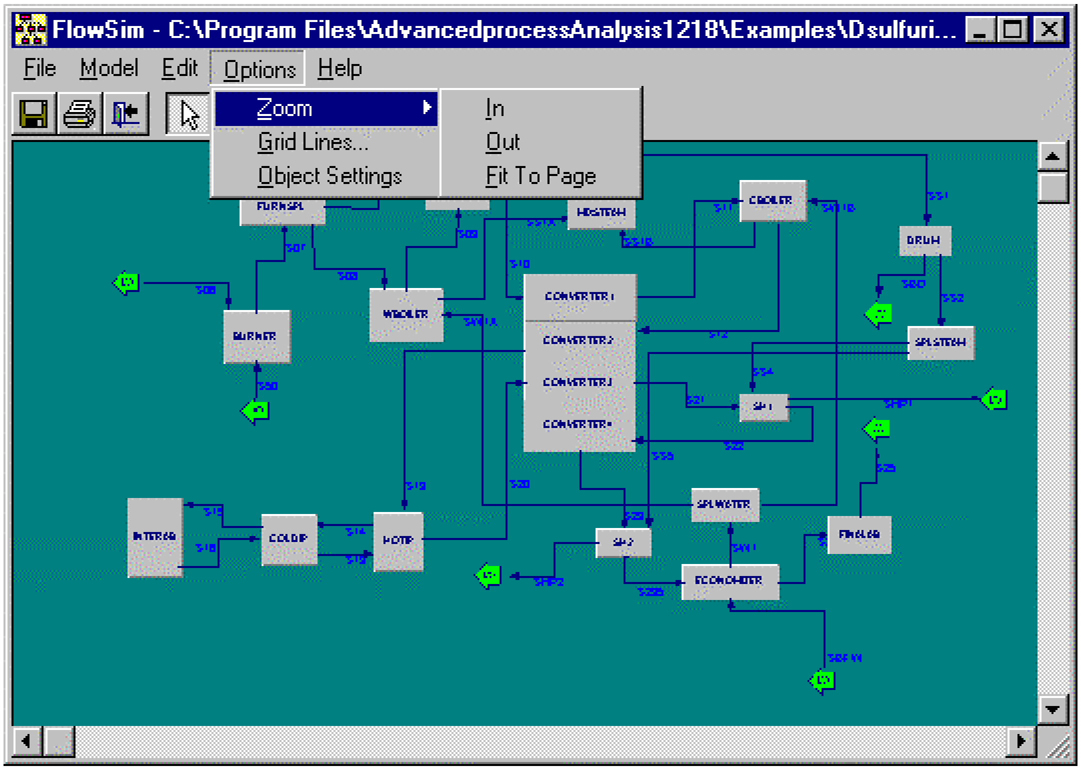
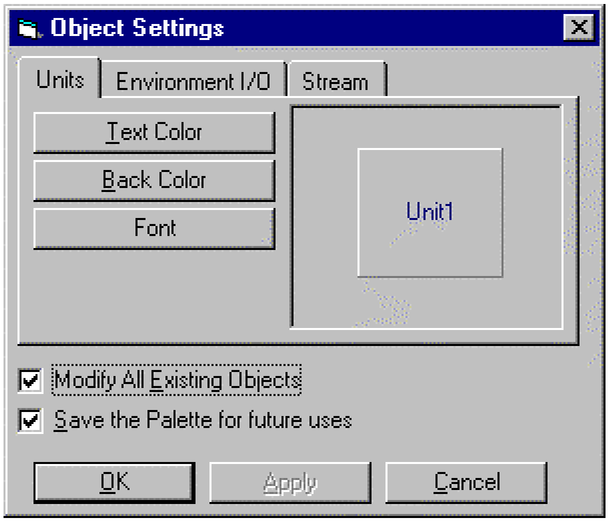


Figure 21 The Options Menu



☑ Modify All Existing Objects

☑ Save the Palette for future uses

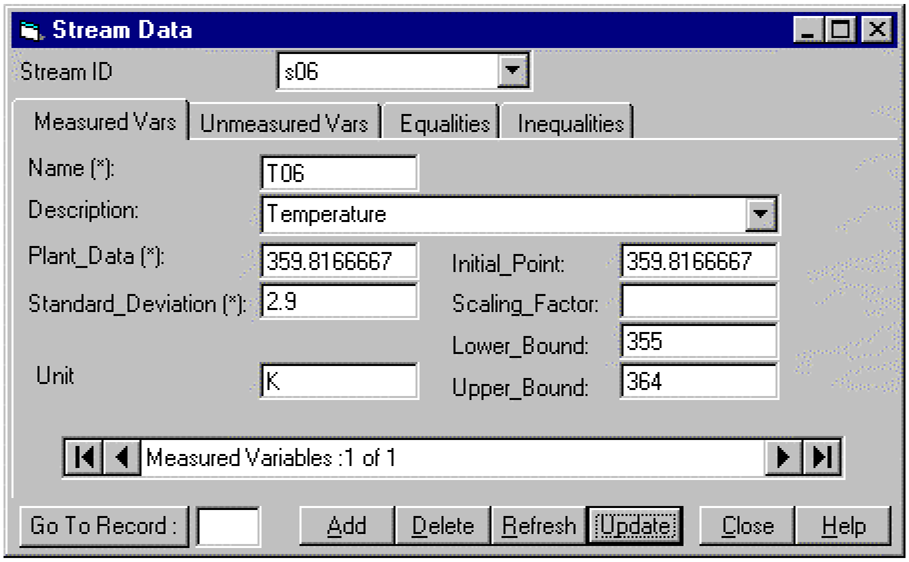
Figure 22 Object Settings Window

The ‘Options’ menu in the Flowsim screen is shown in Figure 21. The zoom option can be used to change the magnification by zooming in and out. The ‘zoom to fit’ option will automatically select the appropriate magnification so that the diagram occupies the entire screen. ‘Grid Lines’ command can be used to display grid lines on the FlowSim screen and to change the spacing between the grid lines. The ‘Object settings’ command is useful to change the appearance of all the units and streams in the FlowSim screen. The object settings window is shown in Figure 22. To change settings for all the streams, click on the streams tab. To change settings for all the environment I/O units, click on the ‘Environment I/O’ tab. If you want the changes to remain effective even after you close the application, you must select ‘Save the palette for future uses’ box.

Once you have drawn a stream, the data associated with the stream can be entered by clicking on the data option in the edit menu or by double clicking on the stream. Let us enter the data associated with the stream s06. When you double click on this stream, a data form is opened. This is shown in Figure 23.

To enter the measured variables associated with the stream, the ‘add’ button should be clicked. When the ‘add’ button is clicked, the caption of the Refresh button changes to ‘Cancel’. Then the information about the variable such as the name of the variable, the plant data, the standard deviation of the plant data should be entered. The description, initial point, scaling factor, lower and upper bounds and the unit of the variable are optional.

The changes can be recorded to the model by clicking on the ‘Update’ button or can be cancelled by clicking on the ‘Cancel’ button. When the update button is clicked, the caption of the cancel button reverts back to ‘Refresh’. The Stream Data Window with the information appears as shown in Figure 23. In this way, all the other measured variables associated with the stream ‘s06’ can be entered.



Stream ID: s06

Name (*): T06

Description: Temperature

Plant_Data (*): 359.8166667

Initial_Point: 359.8166667

Standard_Deviation (*): 2.9

Scaling_Factor:

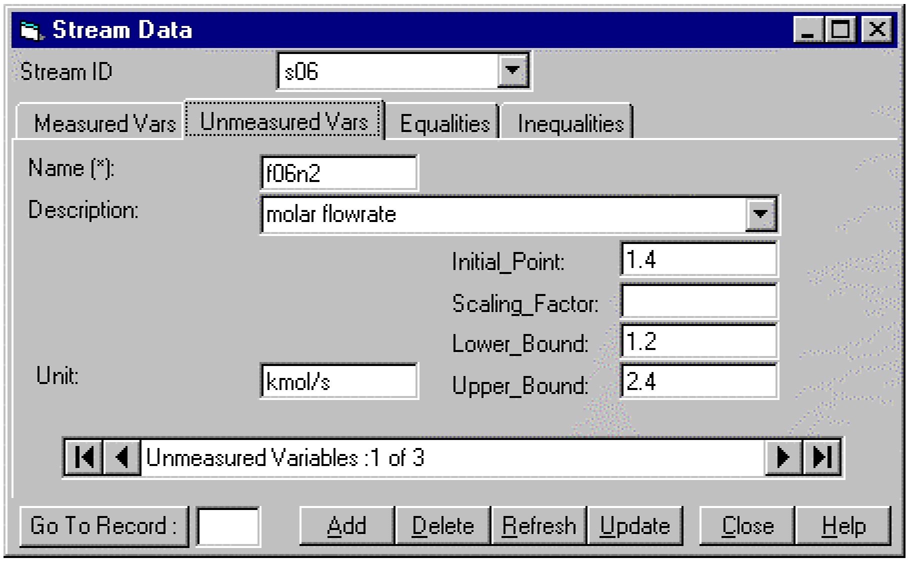
Lower_Bound: 355

Upper_Bound: 364

Unit: K

Measured Variables :1 of 1

Figure 23 Stream Data Window



Stream ID: s06

Name (*): f06n2

Description: molar flowrate

Initial_Point: 1.4

Scaling_Factor:

Lower_Bound: 1.2

Unit: kmol/s

Upper_Bound: 2.4

Unmeasured Variables :1 of 3

Figure 24 Unmeasured Variables Tab in the Stream Data Window

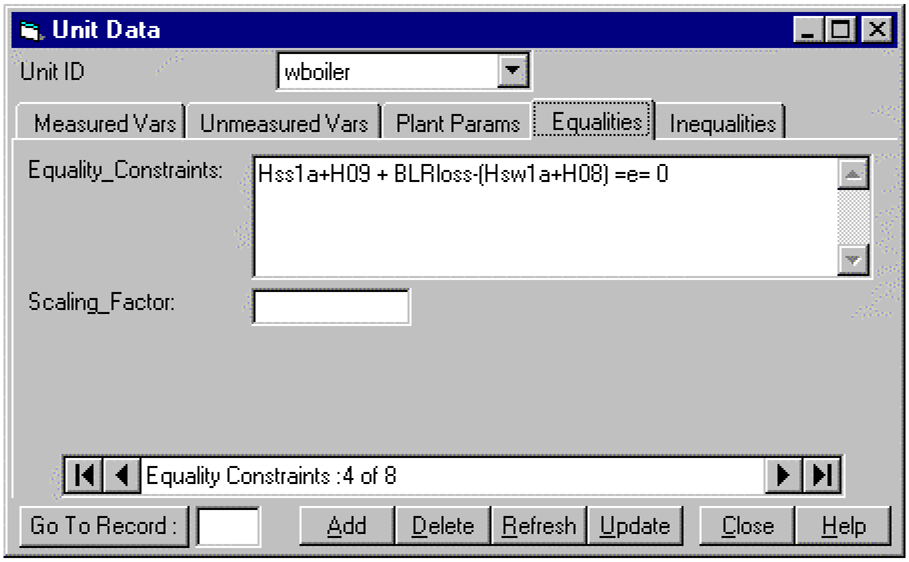
To enter the unmeasured variables associated with the stream, click on the ‘Unmeasured Vars’ tab. As explained above for the measured variables, click on the add button in the stream data window. Enter the name, initial point of the unmeasured variable. The bounds, scaling factor, description and unit of the variable are optional. The Stream Data window with the unmeasured variable data is shown in Figure 24.

To move to a particular variable, enter the record number in the box adjacent to ‘Go to Record’ button. Then press ‘enter’ or click on the ‘Go to Record’ button to move to that variable. To delete a variable, first move to that variable and then click ‘Delete’. To return to the main screen, click on the ‘close’ button.

To enter the data associated with a unit, double click on the unit. When you double click on the unit, a data form similar to the one shown in Figure 23 is opened. The measured variables, unmeasured variables are entered in the same way as for the streams.

Let us proceed to enter the equality constraints for the waste heat boiler unit. Click on the Equalities tab in the Unit Data window to enter the equality constraints.

Let us enter the energy balance equation for the waste heat boiler. This equation is given in Appendix A. Click on the add button on the Unit Data window. Enter the equation in the box provided and click ‘Update’. Note the use of ‘=e=’ in place of ‘=’ as required by the GAMS programming language. The screen now looks as shown in Figure 25a.



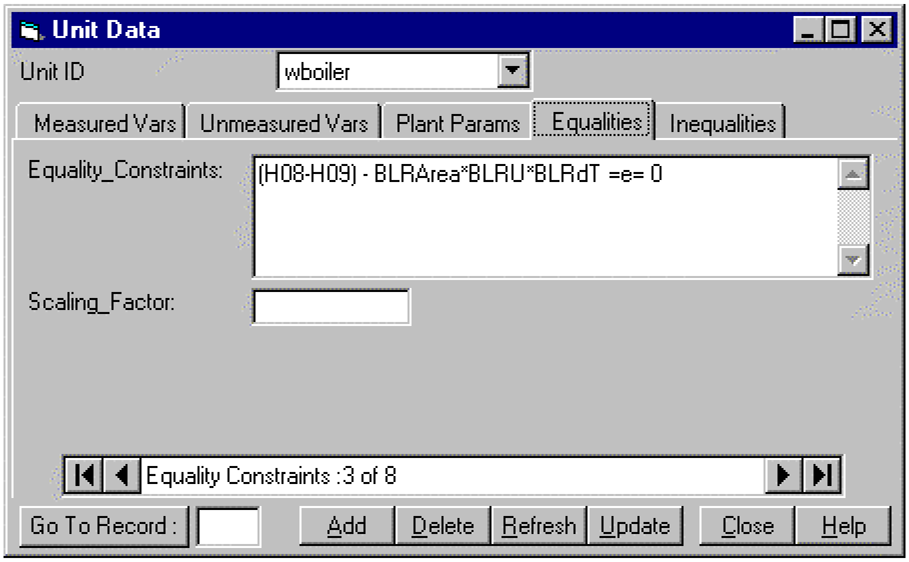
Unit ID: wboiler

Equality_Constraints: Hss1a+H09 + BLRloss-(Hsw1a+H08) =e= 0

Scaling_Factor:

Equality Constraints :4 of 8

Figure 25.a: Equality Constraints Tab in the Unit Data Window



Unit ID: wboiler

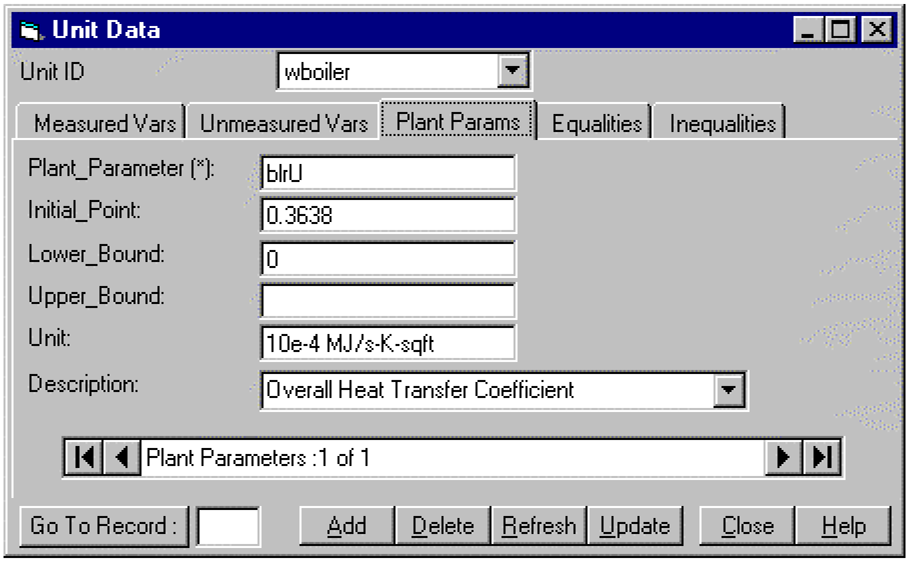
Equality_Constraints: (H08-H09) - BLRArea*BLRU*BLRdT =e= 0

Scaling_Factor:

Equality Constraints :3 of 8

Figure 25.b: Equality Constraints Tab in the Unit Data Window

Let us enter the heat transfer equation for the waste heat boiler. This equation is also given in Appendix A. The Equality constraints tab in the Unit Data window for the waste heat boiler with this equation is shown in Figure 25.b.



Unit ID: wboiler

Plant_Parameter (*): blrU

Initial_Point: 0.3638

Lower_Bound: 0

Upper_Bound:

Unit: 10e-4 MJ/s-K-sqft

Description: Overall Heat Transfer Coefficient

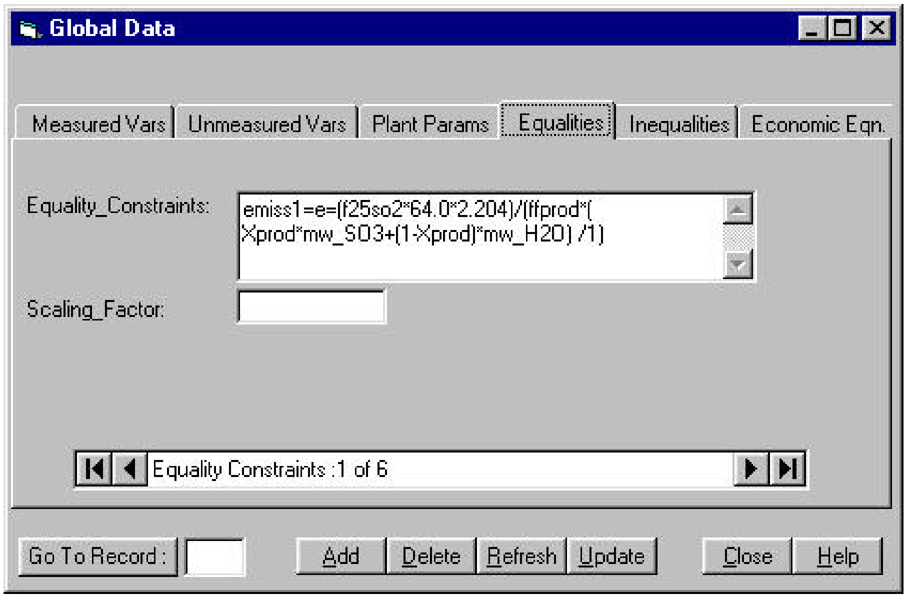
Plant Parameters :1 of 1

Figure 26 Plant Parameters tab in the Unit Data window

Unit Data window has an extra tab for entering the parameters in the model, which are associated with that particular unit. Let us enter the parameter for the waste heat boiler unit. Double click on the unit to open the Unit Data window. In the Unit Data window, click on the ‘Plant Params’ tab. Click on the ‘Add’ button. The parameter name and the initial point are required. Enter ‘blru’ as the parameter name. This is overall heat transfer coefficient of the boiler. The bounds, description and the unit of the parameter are optional. The Unit Data window with the parameter information is shown in Figure 26.

A. Global Data

If there are variables, parameters and equations that do not belong to either a unit or a stream, then they can be entered in the Global Data window. This includes the economic model and the equations to evaluate emissions and energy use. To enter this global data, double click on the background of the flowsheet diagram or click on the ‘Global Data’ option in the Model menu.



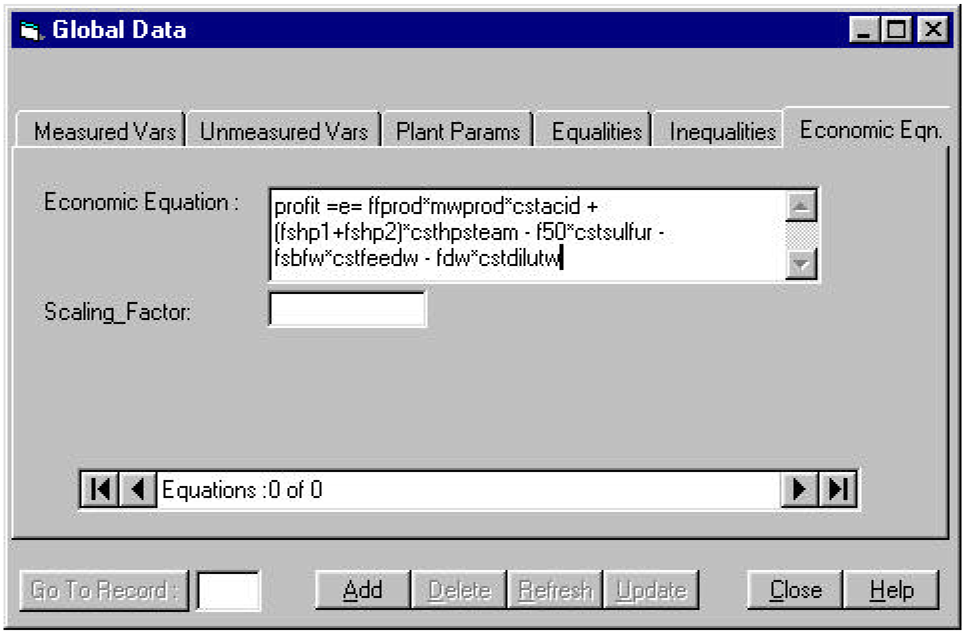
Equality_Constraints: `emiss1=e=(f25so2*64.0*2.204)/(ffprod*( Xprod*mw_SO3+(1-Xprod)*mw_H2O) /1)`

Scaling_Factor:

Figure 27.a Equalities Tab in the Global Data Window

The Global Data window in Figure 27 shows an equation that calculates the emissions, emiss1, from the process when the process is optimized. This equation is explained in section III. Also, equality constraints can be added in this window.

The last tab in the global data window is for the Economic Equations. These are equations, which can be used as the economic model and the left-hand side of one of these equations is specified in on-line optimization as discussed in Section VI. For the contact process, let us enter the equation that defines the profit function for the whole process. Click on the 'add' button and enter the equation shown in Figure 48.b. The variable 'profit' will be used later to specify the objective function for economic optimization. As seen in Figure 27.b, the profit function is equal to the product stream flowrates multiplied by their sales coefficients subtracted by the input stream flowrates multiplied by their cost coefficients.



Economic Equation : profit =e= ffprod*mwprod*cstacid + (fshp1+fshp2)*csthpsteam - f50*cstsulfur - fsbfw*cstfeedw - fdw*cstdilutw

Scaling_Factor:

Equations :0 of 0

Figure 27.b The Economic Equations Tab of Global Data

B. Tables

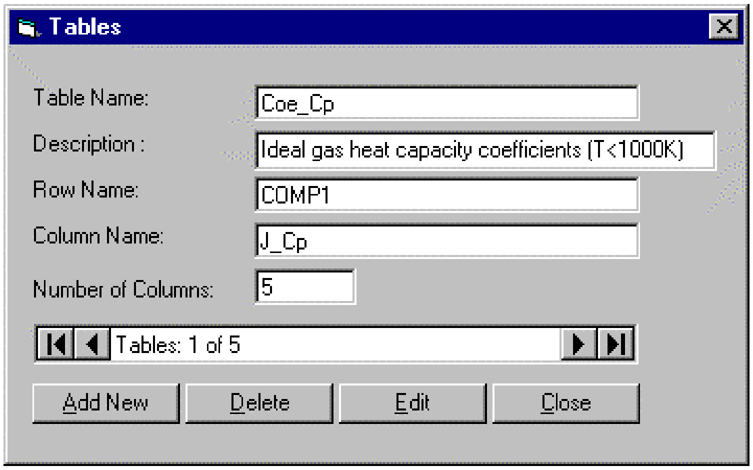


Table Name: Coe_Cp

Description : Ideal gas heat capacity coefficients (T<1000K)

Row Name: COMP1

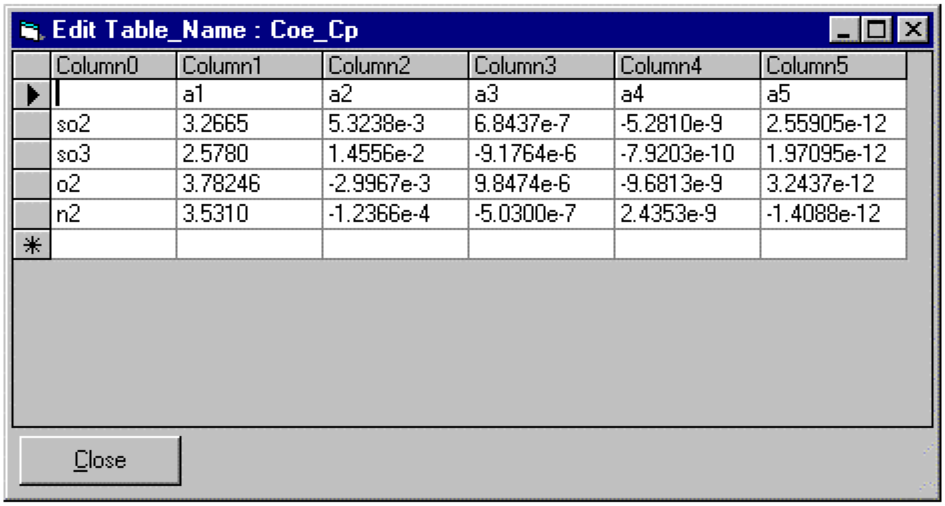
Column Name: J_Cp

Number of Columns: 5

Tables: 1 of 5

Figure 28 Tables Window

If there are constant coefficients used in the constraints equations, they can be defined as a table. These constant coefficients are grouped in sets, and they can be defined using concise names to refer their values in the equations before an equation definition. Let us create a new table for the Contact model. Click on the ‘Tables’ option in the model menu to open the Tables window, which is shown in Figure 28. Then click on the ‘Add New’ button in the tables window to activate the window. As soon as ‘Add New’ button is clicked, the caption of the ‘Add New’ button changes to ‘Save’ and that of ‘Delete’ changes to ‘Cancel’. Then the general information of a table: the name of the table, rows and columns as well as the number of columns, must be



Column0	Column1	Column2	Column3	Column4	Column5
	a1	a2	a3	a4	a5
so2	3.2665	5.3238e-3	6.8437e-7	-5.2810e-9	2.55905e-12
so3	2.5780	1.4556e-2	-9.1764e-6	-7.9203e-10	1.97095e-12
o2	3.78246	-2.9967e-3	9.8474e-6	-9.6813e-9	3.2437e-12
n2	3.5310	-1.2366e-4	-5.0300e-7	2.4353e-9	-1.4088e-12

Figure 29 Edit Table Window

entered from in the window. The name of the table stands for the name of the coefficient group. The names of rows and columns are the set names of the sub-components. After entering the table information, the ‘Save’ button should be clicked to save the changes.

To enter data in a table, click on the ‘Edit’ button. The Edit Table window is opened names and numerical values of constant coefficients. The edit table window for the table ‘Coe_Cp’ is shown in Figure 29. Clicking the ‘Close’ button will update the table and close the ‘Edit table’ window. An existing table can be edited or deleted by selecting the table and then clicking ‘Edit’ or ‘Delete’.

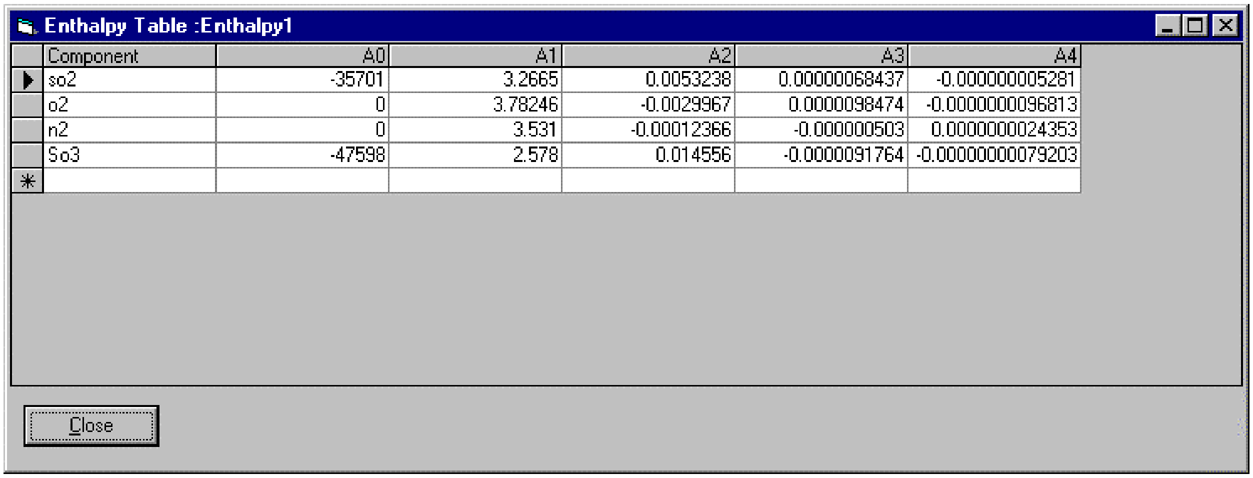
C. Enthalpies

The enthalpy of a stream usually is expressed as a polynomial function of temperature. This function appears repeatedly in the plant model with the same coefficients, which have different numerical values for each chemical component. An example is:

$$h_i = a_{0i} + a_{1i}T + a_{2i} T^2 + a_{3i} T^3 + a_{4i} T^4 + a_{5i} T^5$$

where there are six coefficients, a_{0i} to a_{5i}, for component i.

An enthalpy window can be used to store enthalpy coefficients for a group of components. To create an enthalpy, click on the ‘Enthalpies’ option in the model menu to open the Enthalpy window. Then click on the ‘New Enthalpy’ button in the Enthalpy window. As soon as the user clicks on ‘New Enthalpy’, an input window prompts the user to enter the name of the enthalpy table. An enthalpy table with the given name is created, and an input screen for entering the component information (name, bounds and the coefficients) is displayed. The user can add coefficients to the enthalpy by clicking on the ‘Add Coef’ button. An enthalpy table can be deleted by clicking on the ‘Remove Enthalpy’ button. The enthalpy window is shown in



Component	A0	A1	A2	A3	A4
so2	-35701	3.2665	0.0053238	0.00000068437	-0.000000005281
o2	0	3.78246	-0.0029967	0.0000098474	-0.0000000096813
n2	0	3.531	-0.00012366	-0.000000503	0.0000000024353
So3	-47598	2.578	0.014556	-0.0000091764	-0.00000000079203

Figure 30: Enthalpy Window

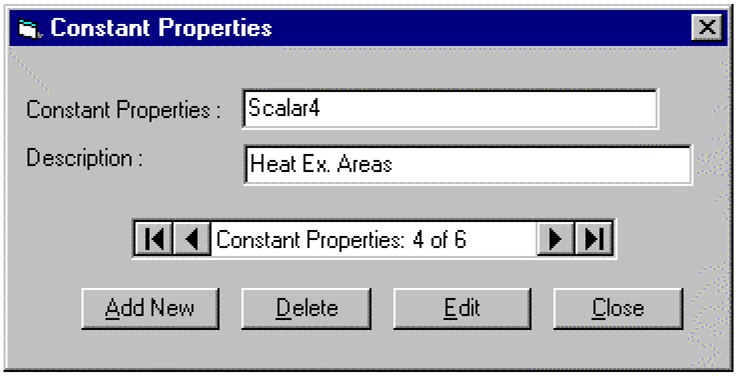
Figure 30. The enthalpy formula for the selected component can be seen at the bottom of the enthalpy window.

NOTE: While entering the Enthalpy values, add the values in the order of reactants followed by product components i.e. SO2,O2 followed by SO3 .

D. Constant Properties

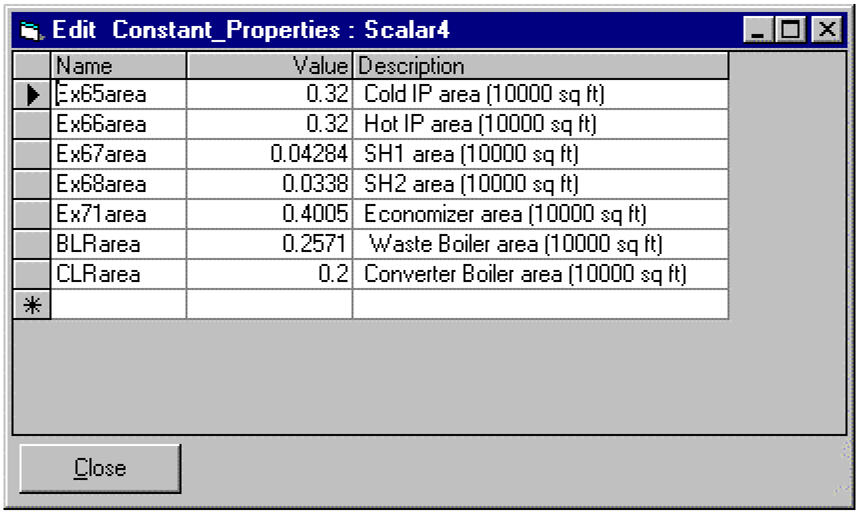
The Constant Property window is where a list of constants is stored. Clicking on the 'Constants' option in the model menu opens the Constant Property window as shown in Figure 31. To create a set of constant properties, click on the 'Add New' button in Constant Property window to activate the window. As soon as 'Add New' button is clicked, the caption of the 'Add New' button changes to 'Save' and that of 'Delete' changes to 'Cancel'. Then the general information of a constant property: the name and an optional description must be entered in the Constant Property window.

After entering the constant property information, the 'Save' button should be clicked to save the changes.



Constant Properties : Scalar4
Description : Heat Ex. Areas

Figure 31 Constant Properties Window

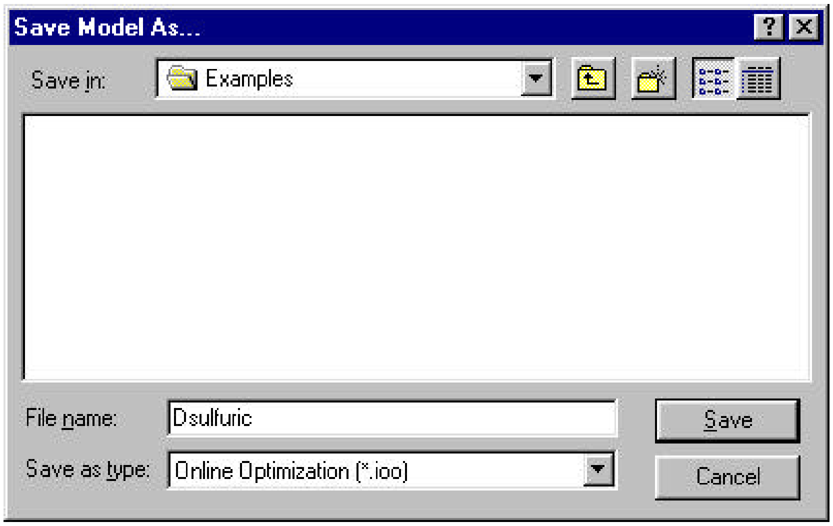

Edit Constant_Properties : Scalar4

Name	Value	Description
Ex65area	0.32	Cold IP area (10000 sq ft)
Ex66area	0.32	Hot IP area (10000 sq ft)
Ex67area	0.04284	SH1 area (10000 sq ft)
Ex68area	0.0338	SH2 area (10000 sq ft)
Ex71area	0.4005	Economizer area (10000 sq ft)
BLRarea	0.2571	Waste Boiler area (10000 sq ft)
CLRarea	0.2	Converter Boiler area (10000 sq ft)

Figure 32 Edit Constant Property Window

To enter the data in the constant property window, click on the ‘Edit’ button. The Edit Constant Property window is opened for entering the numerical values of the constants. The name of the constant, the corresponding numerical value and an optional description. The Edit Constant Property window is shown in Figure 32.

After entering all of the above information, the model is complete. Save the changes by clicking on the ‘Save’ option in the File menu. If you click ‘Exit’ without saving the model, a message is displayed asking whether you want to save the changes or not. The ‘Print’ option in the File menu when clicked, prints the flowsheet diagram. When ‘Exit’ button is clicked, Flowsim window is closed and the user is taken back to the Advanced Process Analysis Desk.


Save Model As...

Save in: Examples

File name: Dsulfuric

Save as type: Online Optimization (*.ioo)

Figure 33 Save Model As Dialog Box

The development of the process model using Flowsim has been completed. The equations, parameters and constants have been stored in the database as shown in Figure 1. Save the model using the 'Save As' option in the File menu shown in Figure 14. A 'Save Model As' dialog box shown in Figure 141 is opened. Save the model as 'Dsulfuric.ioo' in the 'Examples' subdirectory of the program folder.

The process model developed above needs to be validated to make sure that it is representing the actual process accurately and it does not have any mistakes. This can be done by using the model to carry out a simulation and then comparing the results with the design data for the process. If the design data is not available, an alternative solution is to use the combined gross error detection and data reconciliation step of on-line optimization to check the model validity. The plant operating data obtained from the distributed control system can be used for this purpose. The reconciled data obtained is compared with the plant data and if the values agree within the accuracy of the data, the model is an accurate description of the actual process. For the contact sulfuric acid process, this strategy is used to validate the model. The combined gross error detection and data reconciliation is the first step of on-line optimization and will be explained in the next section.

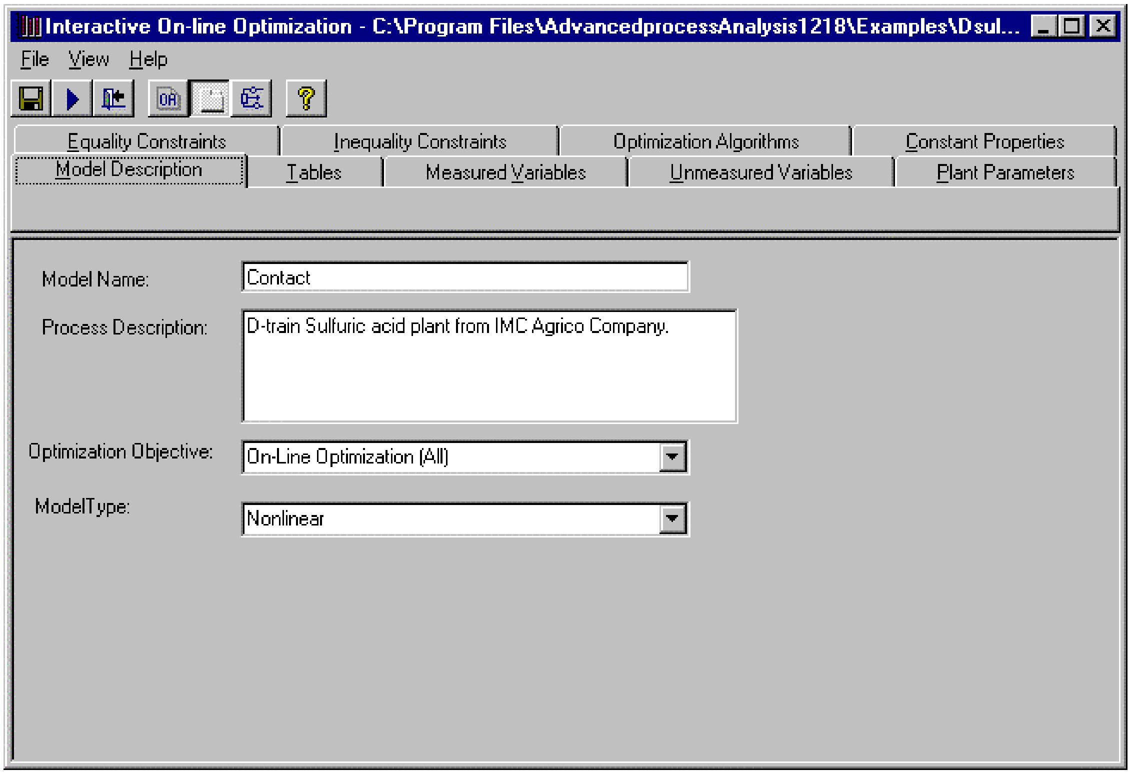
The next step of the Advanced Process Analysis System is on-line optimization. The 'On-line Optimization' button in Figure 10 should be now clicked to open the On-line Optimization program.

VI. USING ONLINE OPTIMIZATION PROGRAM

Upon clicking the 'On-line Optimization' button, On-line Optimization main window is displayed with the Model Description window as shown in Figure 34.

The model name and the description were entered in the Flowsim program. This Model Description window also includes the Optimization Objective and Model Type. The optimization objective can be selected from the drop-down list of 'Optimization Objective' . The five selections are: 'On-line Optimization (All)', 'Data Validation', 'Parameter Estimation', 'Economic Optimization' and 'Parameter Estimation and Economic Optimization'. Let us choose the 'Online Optimization (All)' option for the optimization objective. The model type of the plant model must be specified as either 'Linear' or 'Nonlinear' from the drop-down list. Let us choose 'Nonlinear' as the model type for the Contact model.

When you click on the View menu in the Model Description window, a pull down menu is displayed as shown in Figure 35. The View menu includes commands for the All Information mode, The Online Optimization Algorithms and Flow sheet diagram. The 'All Information' modes is used to switch between windows. The 'All Information' mode displays the different windows combined together into one switchable window. The Flowsheet diagram option is used to view the flowsheet diagram, which is drawn using the flowsheet simulation program.



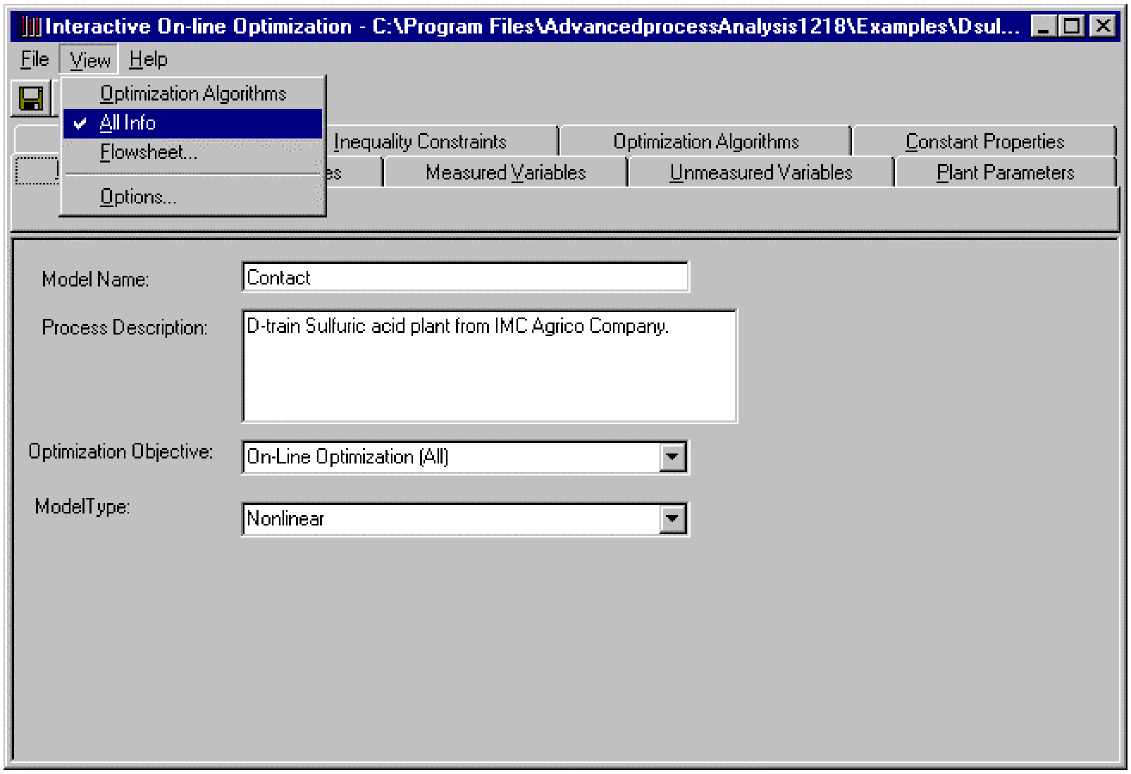
Model Name: Contact

Process Description: D-train Sulfuric acid plant from IMC Agrico Company.

Optimization Objective: On-Line Optimization (All)

ModelType: Nonlinear

Figure 34: Model Description Window



Model Name: Contact

Process Description: D-train Sulfuric acid plant from IMC Agrico Company.

Optimization Objective: On-Line Optimization (All)

ModelType: Nonlinear

Figure 35: View Menu

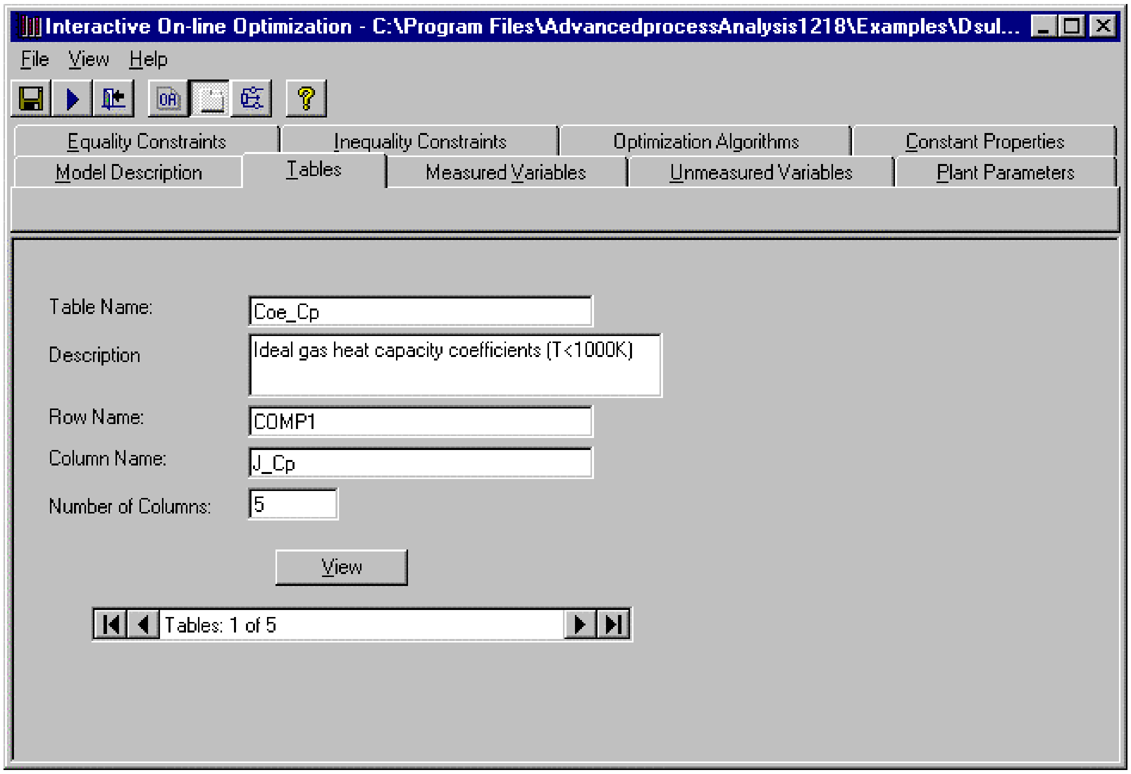


Table Name: Coe_Cp

Description: Ideal gas heat capacity coefficients (T<1000K)

Row Name: COMP1

Column Name: J_Cp

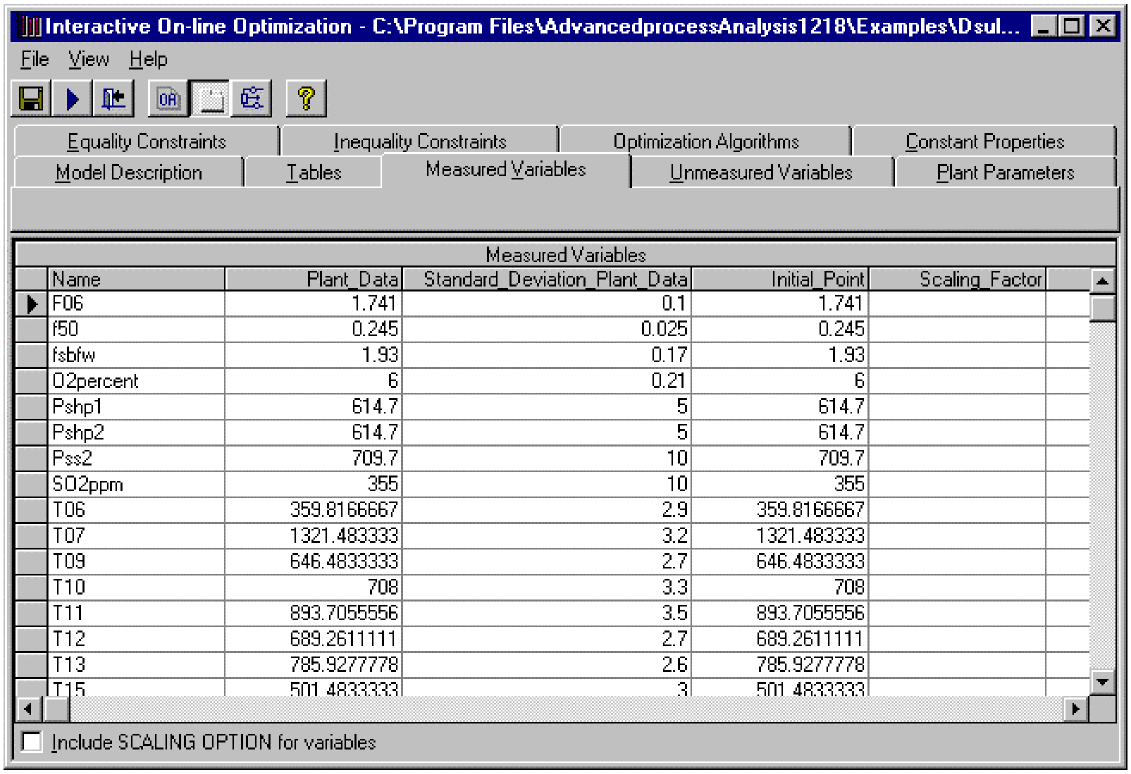
Number of Columns: 5

Figure 36: Tables Window

When the information for the Model Description window is completed, you can proceed to the Tables window by clicking on the Tables tab in the All-Information mode. The tables window is shown in Figure 36 which contains information about the tables which were entered in Flowsim program.

Let us proceed to the Measured Variables window by clicking the Measured Variables tab. The Measured Variables window has a table with twelve columns which display the name, plant data, standard deviation, initial point, scaling factor, lower and upper bounds, stream number, process unit ID, the unit and a short description of the measured variables. The Measured Variables window lists all the measured variables that are associated with all the units and streams in the process model and the global measured variables that were entered in the Flowsim program. The column ‘Process Unit ID’ has the name of the process unit and the column ‘Stream Number’ has the name of the stream with which the variable is associated. The Measured Variables window is shown in Figure 37. In this window, information can only be viewed. All of the data entered in Flowsim can only be viewed using the screens of on-line optimization. To change the data, the user has to go back to Flowsim program.

Then proceed to the Unmeasured variables window by clicking on the Unmeasured Variables tab. The Unmeasured variables window has nine columns for displaying the name, initial point, scaling factor, lower and upper bounds, stream number, process unitID, unit and description of the unmeasured variables. The Unmeasured Variables window lists all the unmeasured variables,

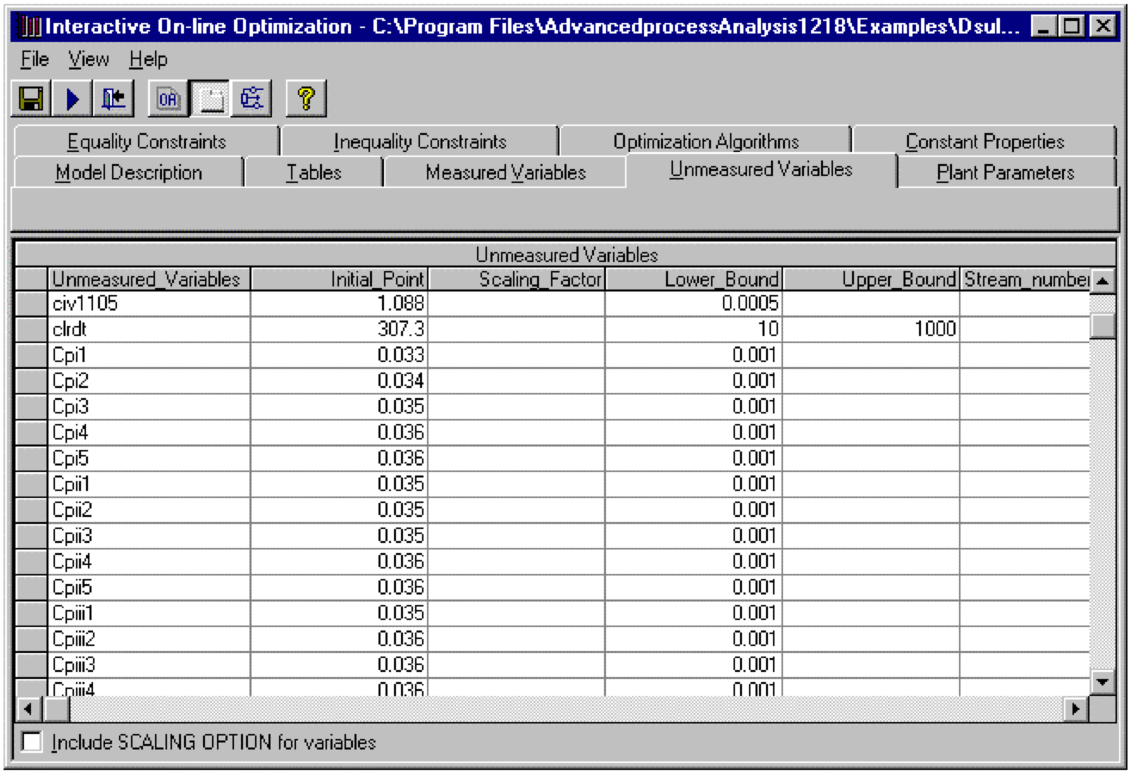


Measured Variables

Name	Plant_Data	Standard_Deviation_Plant_Data	Initial_Point	Scaling_Factor
F06	1.741	0.1	1.741	
f50	0.245	0.025	0.245	
fsbfw	1.93	0.17	1.93	
O2percent	6	0.21	6	
Pshp1	614.7	5	614.7	
Pshp2	614.7	5	614.7	
Pss2	709.7	10	709.7	
SO2ppm	355	10	355	
T06	359.8166667	2.9	359.8166667	
T07	1321.483333	3.2	1321.483333	
T09	646.4833333	2.7	646.4833333	
T10	708	3.3	708	
T11	893.7055556	3.5	893.7055556	
T12	689.2611111	2.7	689.2611111	
T13	785.9277778	2.6	785.9277778	
T15	501.4833333	3	501.4833333	

☐ Include SCALING OPTION for variables

Figure 37: Measured Variables Window

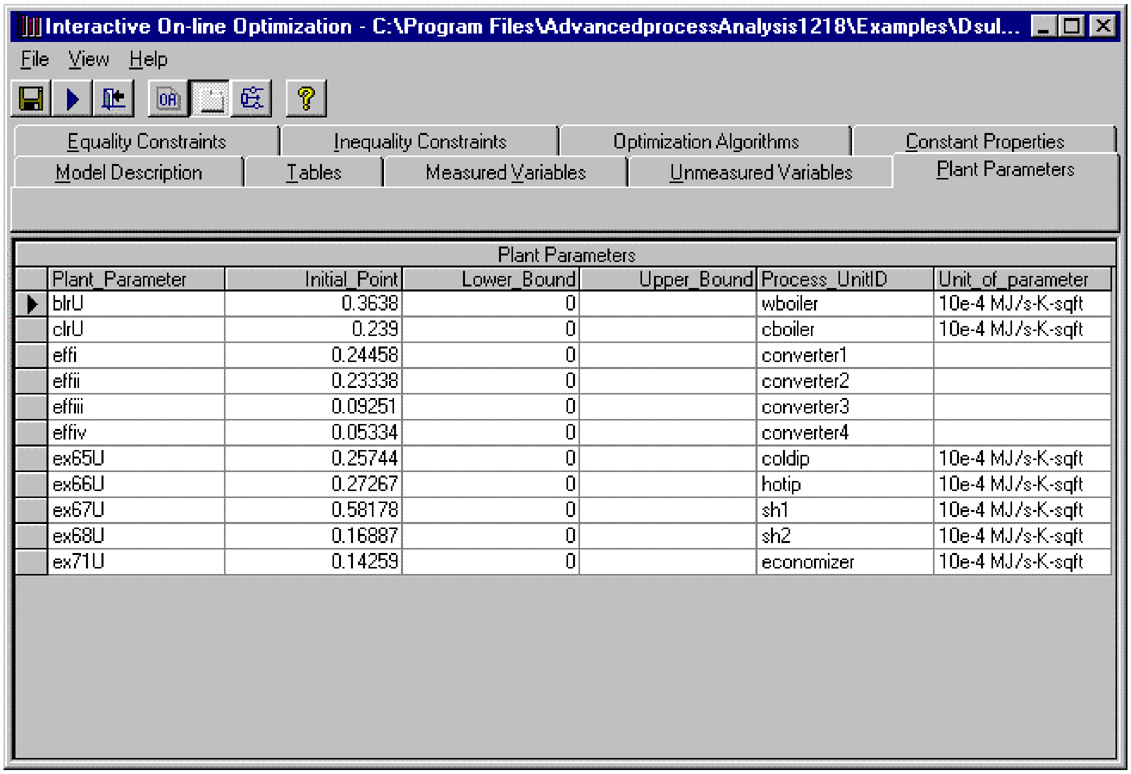


Unmeasured Variables

Unmeasured_Variables	Initial_Point	Scaling_Factor	Lower_Bound	Upper_Bound	Stream_numbe
civ1105	1.088		0.0005		
clrdt	307.3		10	1000	
Cpi1	0.033		0.001		
Cpi2	0.034		0.001		
Cpi3	0.035		0.001		
Cpi4	0.036		0.001		
Cpi5	0.036		0.001		
Cpii1	0.035		0.001		
Cpii2	0.035		0.001		
Cpii3	0.035		0.001		
Cpii4	0.036		0.001		
Cpii5	0.036		0.001		
Cpiii1	0.035		0.001		
Cpiii2	0.036		0.001		
Cpiii3	0.036		0.001		
Cpiii4	0.036		0.001		

☐ Include SCALING OPTION for variables

Figure 38: Unmeasured Variables Window



Plant Parameters

Plant_Parameter	Initial_Point	Lower_Bound	Upper_Bound	Process_UnitID	Unit_of_parameter
blrU	0.3638	0		wboiler	10e-4 MJ/s-K-sqft
clrU	0.239	0		cboiler	10e-4 MJ/s-K-sqft
effi	0.24458	0		converter1	
effii	0.23338	0		converter2	
effiii	0.09251	0		converter3	
effiv	0.05334	0		converter4	
ex65U	0.25744	0		coldip	10e-4 MJ/s-K-sqft
ex66U	0.27267	0		hotip	10e-4 MJ/s-K-sqft
ex67U	0.58178	0		sh1	10e-4 MJ/s-K-sqft
ex68U	0.16887	0		sh2	10e-4 MJ/s-K-sqft
ex71U	0.14259	0		economizer	10e-4 MJ/s-K-sqft

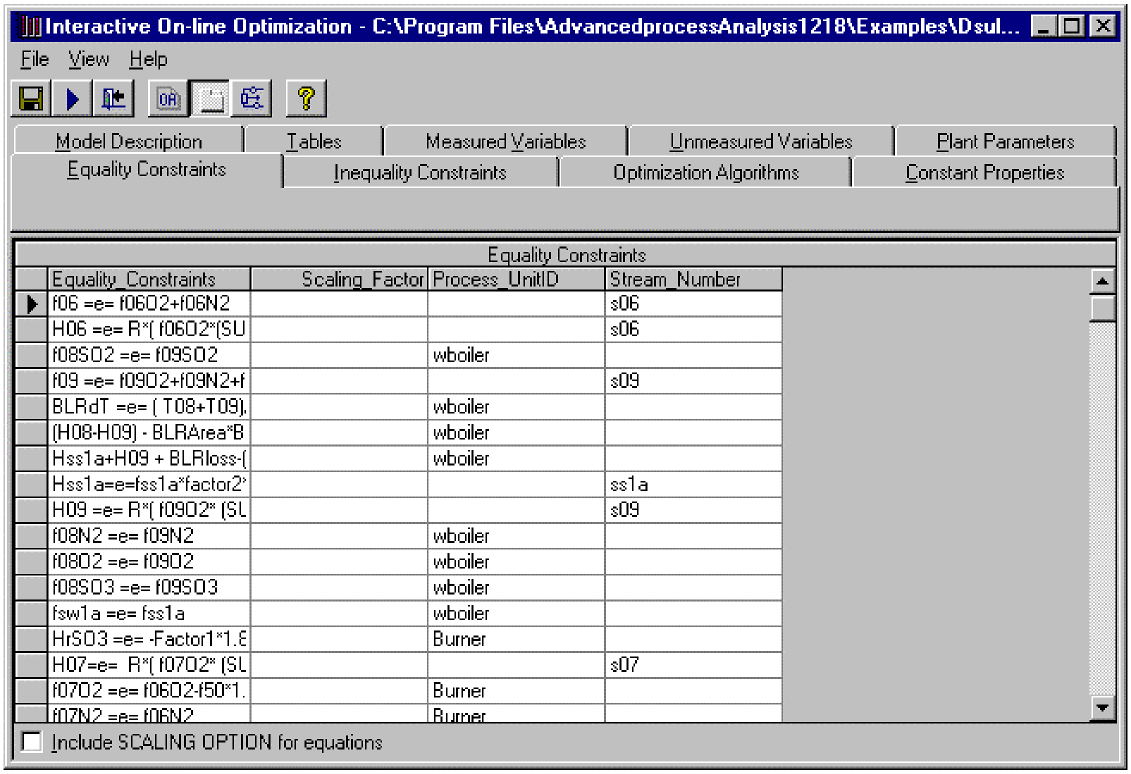
Figure 39: Plant Parameters Window

which were entered in the Flowsim program. The Unmeasured Variables window is shown in Figure 38.

Optimization programs need to have all the variables in the same numerical range, and it may be necessary to scale the variables by adjusting the scaling factors. For the contact model, the unmeasured variables should be scaled. To scale variables using Scaling Option provided by the system, the scale factors must be entered in the Flowsim program and the icon ‘Include Scaling Option for variables’ at the bottom of Figure 38 should be checked. A description of scaling factors and their use is given in Section XI.

Let us proceed to the Plant Parameters window by clicking on Plant Parameters tab. The Plant Parameters window lists all the parameters entered in the Unit and the Global Data window of the Flowsim program. The Plant Parameters window is shown in Figure 39.

Then proceed to the Equality Constraints window. This window has four columns for displaying the constraints, scaling factor, process unitID and stream number. All the equality constraints entered in the Flowsim program are listed in this window. The equality constraints window is shown in Figure 40. The next step is the Inequality Constraints window, which is similar to the Equality Constraints window. The Inequality Constraints window has three columns for displaying the constraints, process unitID and stream number. Scaling factors are not available for inequality constraints.

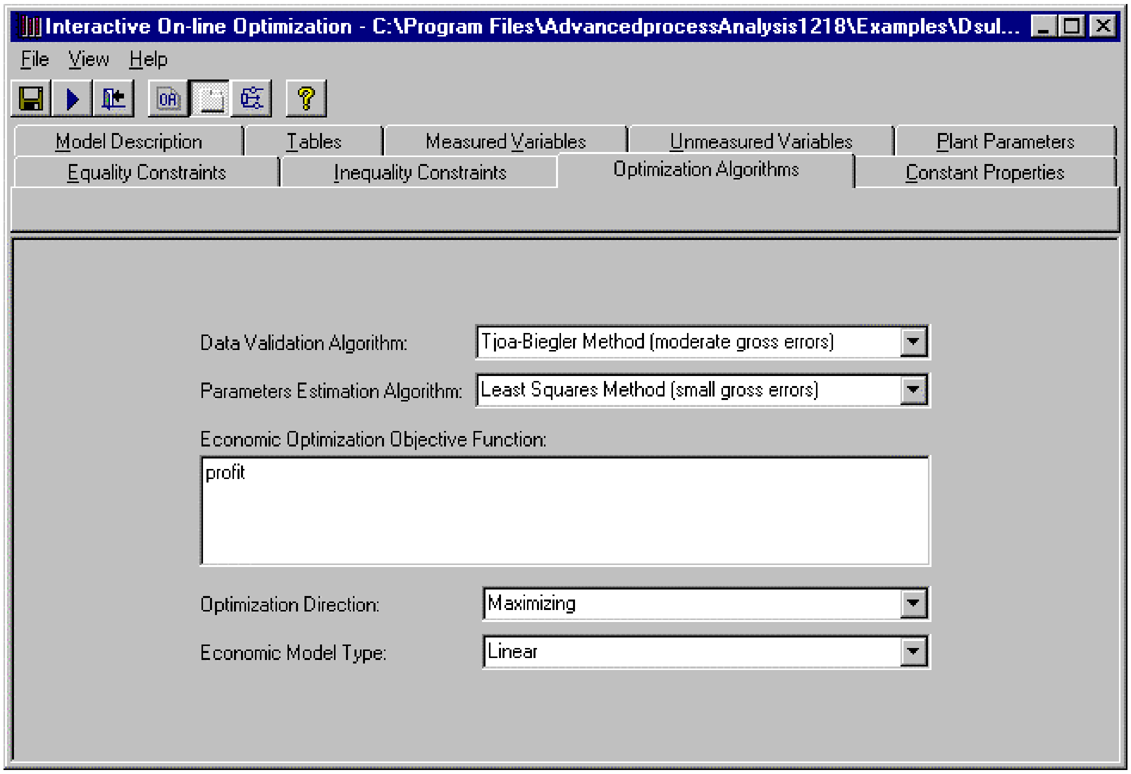


Equality Constraints

Equality_Constraints	Scaling_Factor	Process_UnitID	Stream_Number
f06 =e= f06O2+f06N2			s06
H06 =e= R*(f06O2*(SU			s06
f08SO2 =e= f09SO2		wboiler	
f09 =e= f09O2+f09N2+f			s09
BLRdT =e= (T08+T09)/		wboiler	
(H08-H09) - BLRArea*B		wboiler	
Hss1a+H09 + BLRloss-(		wboiler	
Hss1a=e=fss1a*factor2*			ss1a
H09 =e= R*(f09O2* (SL			s09
f08N2 =e= f09N2		wboiler	
f08O2 =e= f09O2		wboiler	
f08SO3 =e= f09SO3		wboiler	
fsw1a =e= fss1a		wboiler	
HrSO3 =e= -Factor1*1.8		Burner	
H07=e= R*(f07O2* (SL			s07
f07O2 =e= f06O2-f50*1.		Burner	
f07N2 =e= f06N2		Burner	

☐ Include SCALING OPTION for equations

Figure 40 Equality Constraints Window



Data Validation Algorithm: Tjoa-Biegler Method (moderate gross errors)

Parameters Estimation Algorithm: Least Squares Method (small gross errors)

Economic Optimization Objective Function:

profit

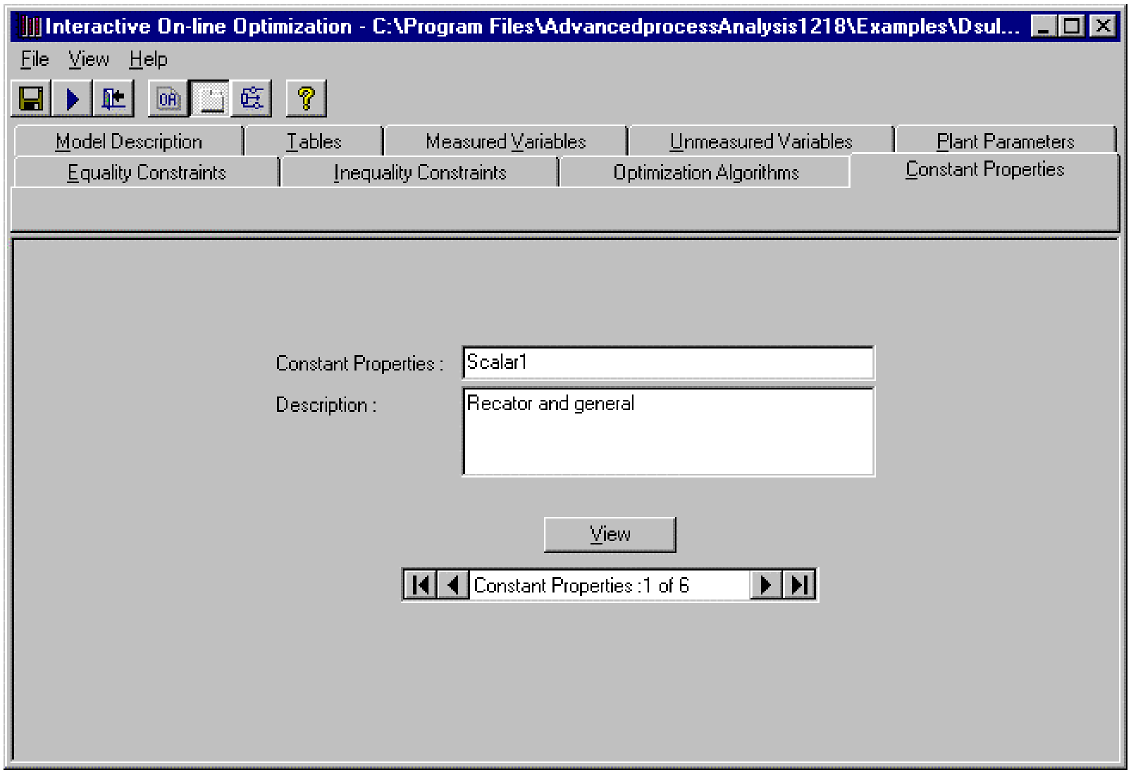
Optimization Direction: Maximizing

Economic Model Type: Linear

Figure 41: Optimization Algorithms Window

Let us proceed to the Optimization Algorithm window shown in Figure 41. This window includes the algorithms for Data Validation and Parameter Estimation, the Objective function for Economic Optimization, the Optimization direction and the Economic Model type. The default options are Tjoa-Biegler's method for data validation and Least Squares method for Parameter Estimation. In the Economic Optimization for the contact process, the objective function is 'profit' defined in Section V in a global economic equation (Figure 27.b). Let us choose the optimization direction to be 'Maximizing' and the Economic Model type to be 'Linear'.

The next step is the Constant Properties window. The constant properties window is shown in Figure 42-A.

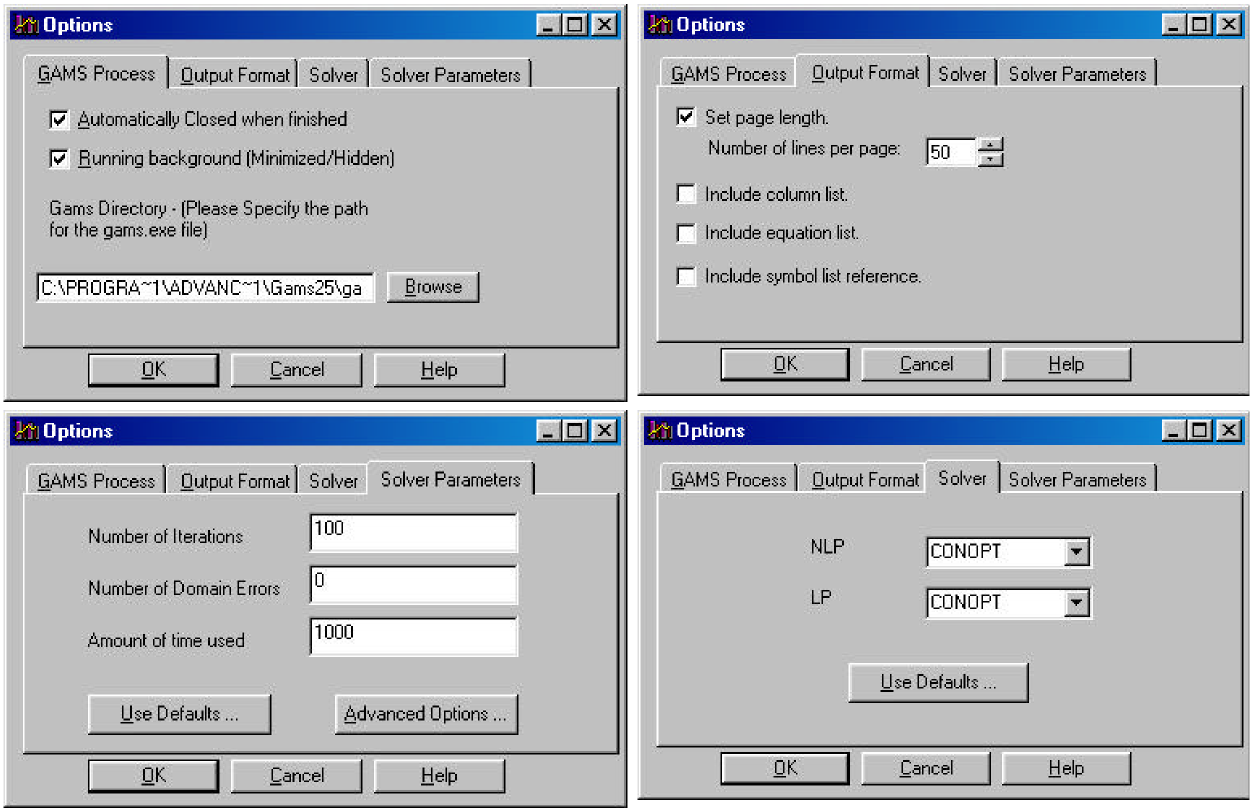


Constant Properties : Scalar1

Description : Recator and general

Constant Properties :1 of 6

Figure 42-A: Constant Properties Window



☑ Automatically Closed when finished

☑ Running background (Minimized/Hidden)

Gams Directory - (Please Specify the path
for the gams.exe file)

C:\PROGRA~1\ADVANC~1\Gams25\ga

☑ Set page length.

Number of lines per page: 50

☐ Include column list.

☐ Include equation list.

☐ Include symbol list reference.

Number of Iterations: 100

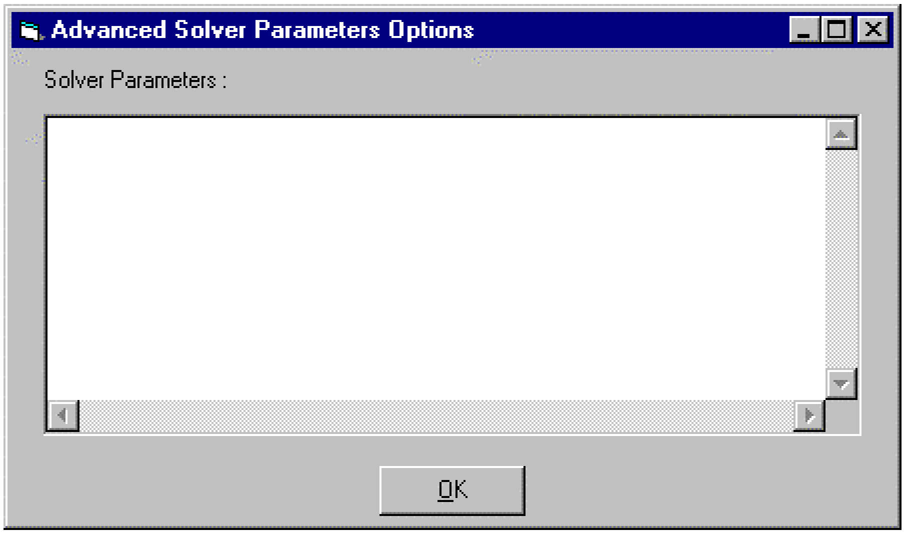
Number of Domain Errors: 0

Amount of time used: 1000

NLP: CONOPT

LP: CONOPT

Figure 42 -B Options



Solver Parameters :

Figure 42-C. Advaced Parameters Options Window

Clicking on the 'Options' item in 'View' menu, opens the Options window as shown in Figure 42-B. General GAMS Process options are set in the 'GAMS Process' tab as shown in the first window of Figure 42-B. The format for the GAMS output can be specified in the 'Output Format' tab as shown in second window of Figure 42-B. LP and NLP values for the Solver can be set in the 'Solver' tab as shown in the third window of Figure 42-B. The default values are CONOPT for both LP and NLP. These default values can be restored by clicking on the 'Use Defaults…' button. Solver Parameters like Number of Iterations, Number of Domain Errors and Amount of Time Used can be specified in the 'Solver Parameters' tab as shown in the fourth window of Figure 42-B. The recommended values for Solver Parameters of the contact process are Number of iterations 1000, Domain Errors 0, and Amount of time used 1000 sec. The default values can be restored by clicking on the 'Use Defaults…' button. Other advanced options can be set by clicking on the 'Advanced Options' button, which brings up the window shown in Figure 42-C.

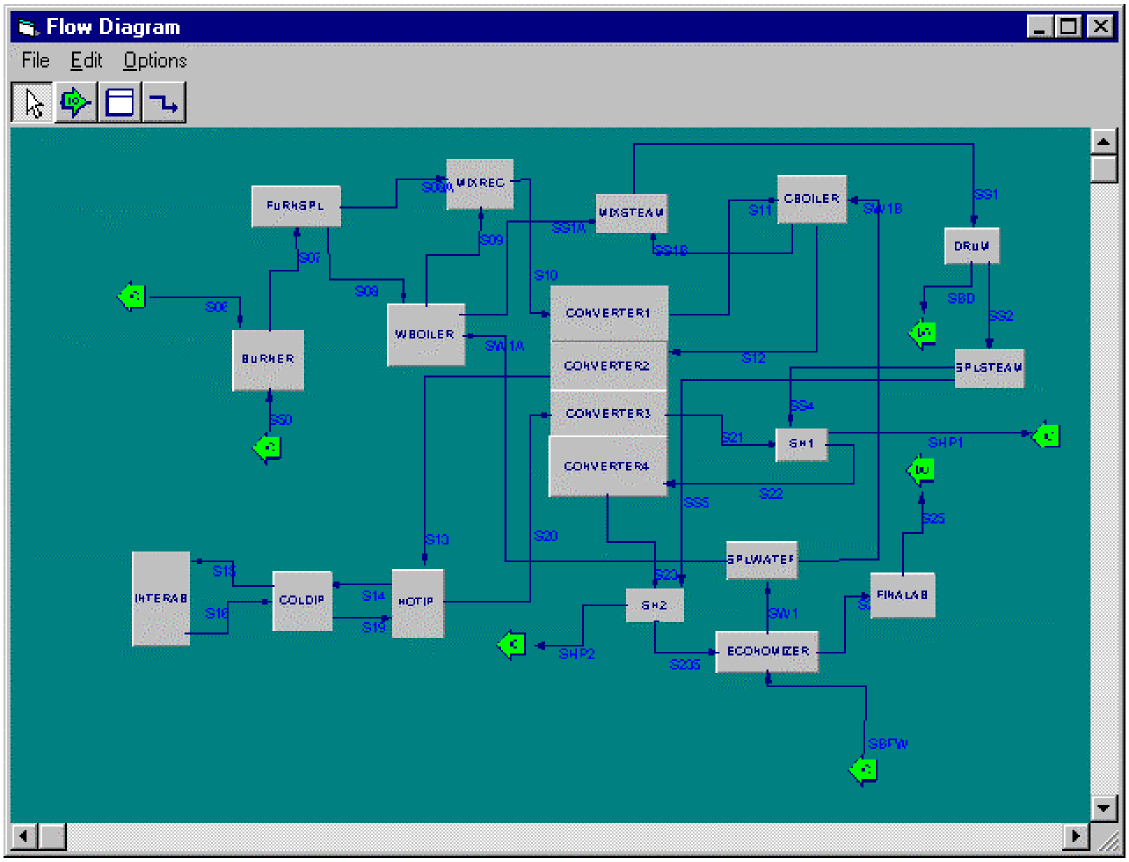
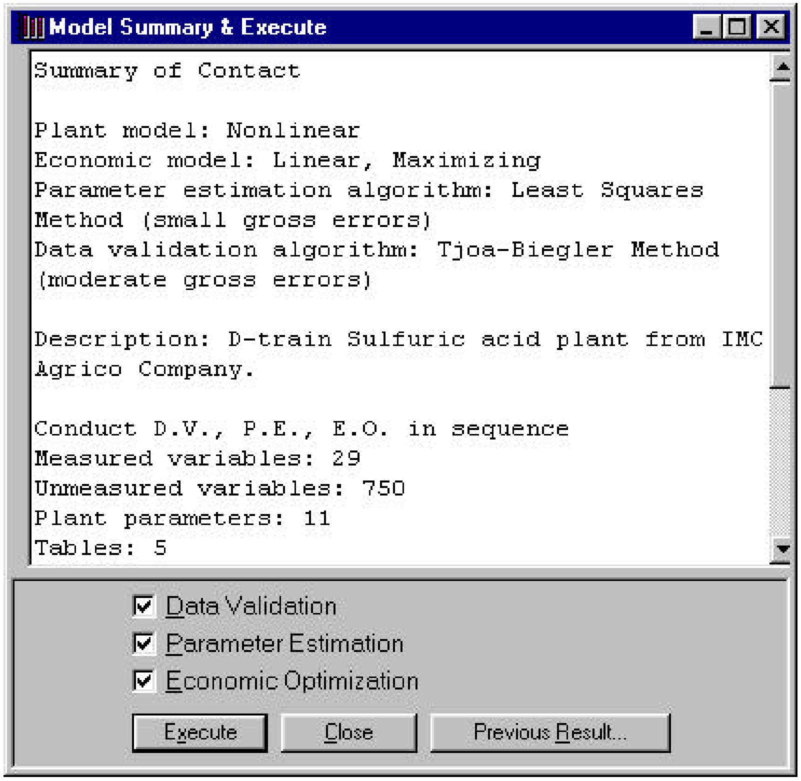


Figure 43: Flowsheet Diagram Window

The flowsheet diagram can be viewed by clicking on the 'FlowSheet Diagram' option in the view menu as shown in Figure 35. The flowsheet cannot be edited in the On-line Optimization program. The flowsheet diagram is shown in Figure 43. Double clicking on a unit opens a data form, which displays all the measured variables, unmeasured variables and plant parameters that are associated with that unit. Similarly double clicking on a stream opens a data form, which displays the measured and unmeasured variables, associated with the stream. The global data can be viewed by double clicking on the background of the flowsheet.

After entering the required information, let us proceed to execute the model. To execute the model, click on the 'Execute' option in the File menu or click on the 'Execute' button in the toolbar. Once the 'Execute' option is clicked the Model Summary and Execute window as shown in Figure 44 is opened. This window gives the summary of the contact process.

When the 'Execute' button in the 'Model Execute and Summary' window is clicked, the program first extracts the model information from the database. Based on this information, it generates the GAMS input files and calls the GAMS solver. The progress of GAMS program execution is shown in Figure 45. This window is automatically closed as soon as the execution is over. When the execution of the program is completed, it displays the results of on-line optimization results in the Output window.



```
Summary of Contact

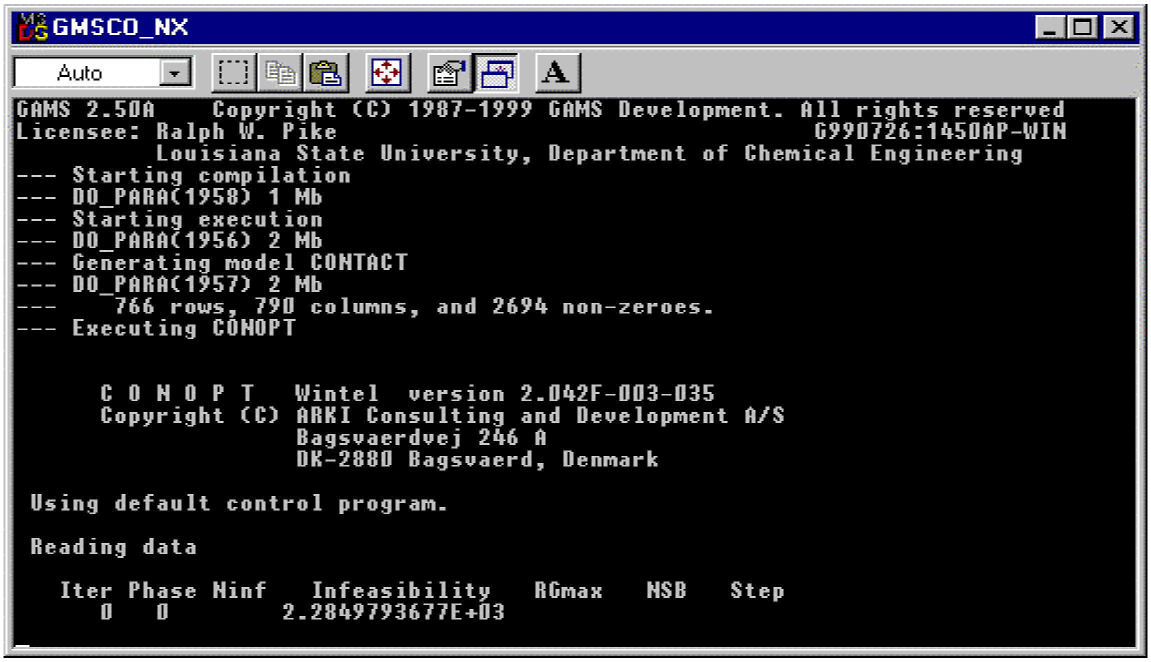
Plant model: Nonlinear
Economic model: Linear, Maximizing
Parameter estimation algorithm: Least Squares
Method (small gross errors)
Data validation algorithm: Tjoa-Biegler Method
(moderate gross errors)

Description: D-train Sulfuric acid plant from IMC
Agrico Company.

Conduct D.V., P.E., E.O. in sequence
Measured variables: 29
Unmeasured variables: 750
Plant parameters: 11
Tables: 5
```

☑ Data Validation
☑ Parameter Estimation
☑ Economic Optimization

Figure 44: Model Execution and Summary Window



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Licensee: Ralph W. Pike                                    G990726:1450AP-WIN
          Louisiana State University, Department of Chemical Engineering
--- Starting compilation
--- DO_PARA(1958) 1 Mb
--- Starting execution
--- DO_PARA(1956) 2 Mb
--- Generating model CONTACT
--- DO_PARA(1957) 2 Mb
---    766 rows, 790 columns, and 2694 non-zeroes.
--- Executing CONOPT


      C O N O P T   Wintel  version 2.042F-003-035
      Copyright (C) ARKI Consulting and Development A/S
                    Bagsvaerdvej 246 A
                    DK-2880 Bagsvaerd, Denmark

 Using default control program.

 Reading data

   Iter Phase Ninf   Infeasibility   RGmax    NSB    Step
      0    0        2.2849793677E+03
```

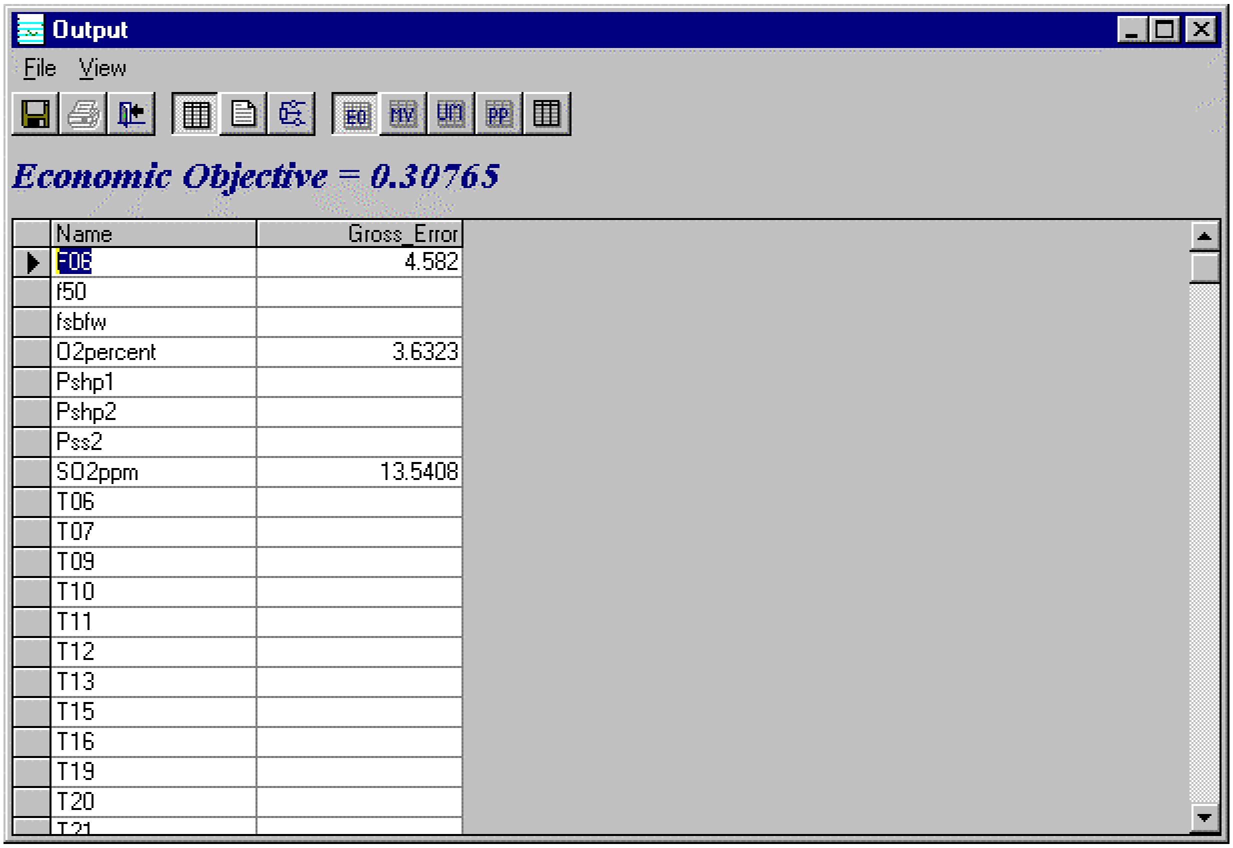
Figure 45. GAMS Program Execution Window

A GAMS licensed software is required to execute this program. This contact plant has 760 constraints, and the free or demonstration version is limited to 300 constraint equations. The results for the optimization case are included. And can be seen by clicking on the button "Previous Results" in figure 44. A licensed version can be obtained from the GAMS Development Corporation(www.gams.com).

After the three programs have been executed, three detailed GAMS output files will be generated by GAMS for the three optimization problems. These files give detailed solutions of the optimization problems for Data Validation, Parameter Estimation and Economic Optimization. Also, a final report is generated by Interactive On-line Optimization system. In the final report, the estimated values of parameters, the reconciled values of process variables, the optimal set points and profit from Economic Optimization are shown. The Output Window with the Final Report is shown in Figure 46. The View menu in the Output window has three options namely Final Report, Full output and Flowsheet.

The Final Report options has five options namely the Economic Objective, Measured Variables, Unmeasured Variables, Plant Parameters and the Stream number as shown in Figure 47. The Economic Objective value is shown in Figure 46.

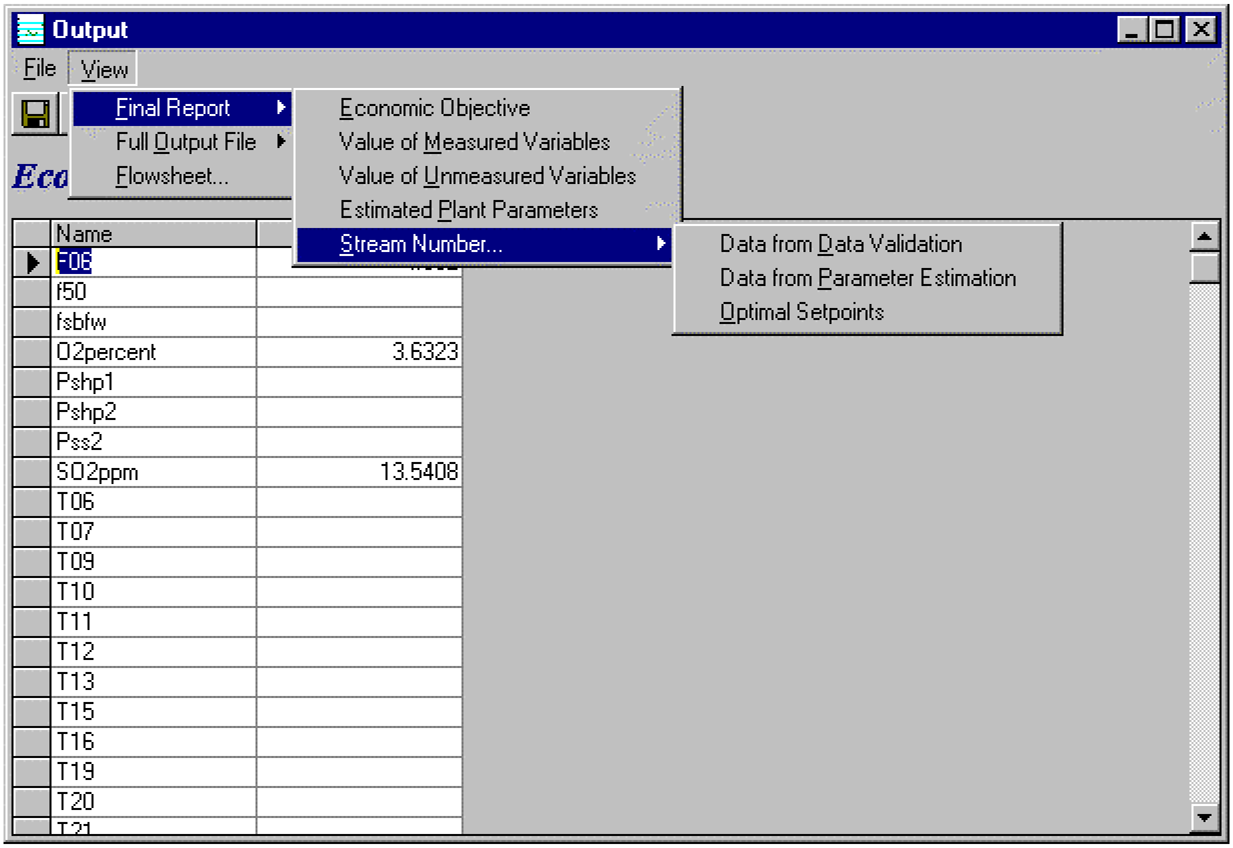
When the option 'Measured Variables' in the Final Report menu is clicked, the system opens a spreadsheet data form which includes the optimal setpoints from economic optimization, reconciled value from Data Validation, reconciled value from Parameter Estimation and the plant data as shown in Figure 48. Clicking on "Plant parameters" in Final Report menu, the system opens a spreadsheet data form that includes the estimated values of plant parameters as shown in Figure 49.



Economic Objective = 0.30765

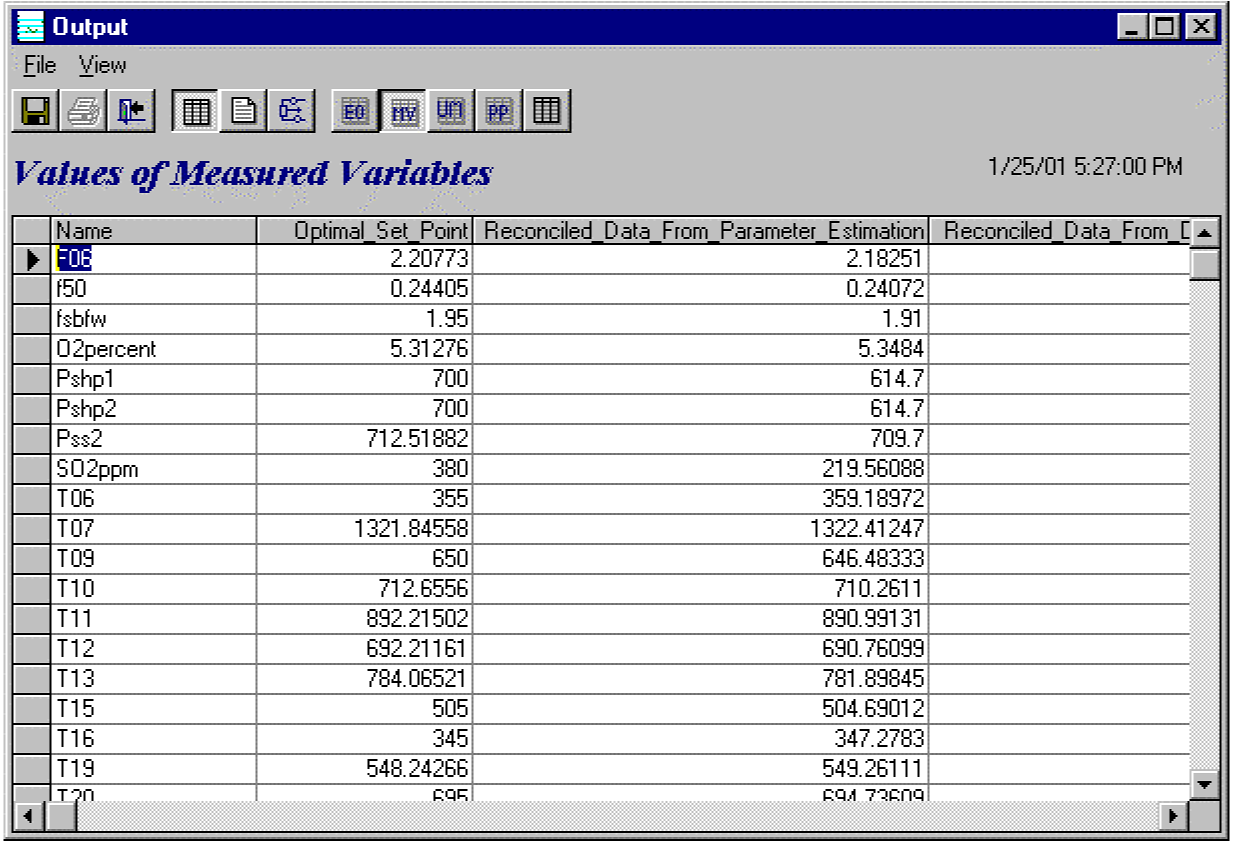
Name	Gross_Error
F06	4.582
f50	
fsbfw	
O2percent	3.6323
Pshp1	
Pshp2	
Pss2	
SO2ppm	13.5408
T06	
T07	
T09	
T10	
T11	
T12	
T13	
T15	
T16	
T19	
T20	

Figure 46: Final Report in the Output Window



Name	
F06	
f50	
fsbfw	
O2percent	3.6323
Pshp1	
Pshp2	
Pss2	
SO2ppm	13.5408
T06	
T07	
T09	
T10	
T11	
T12	
T13	
T15	
T16	
T19	
T20	
T21	

Figure 47: View Menu in the Output Window

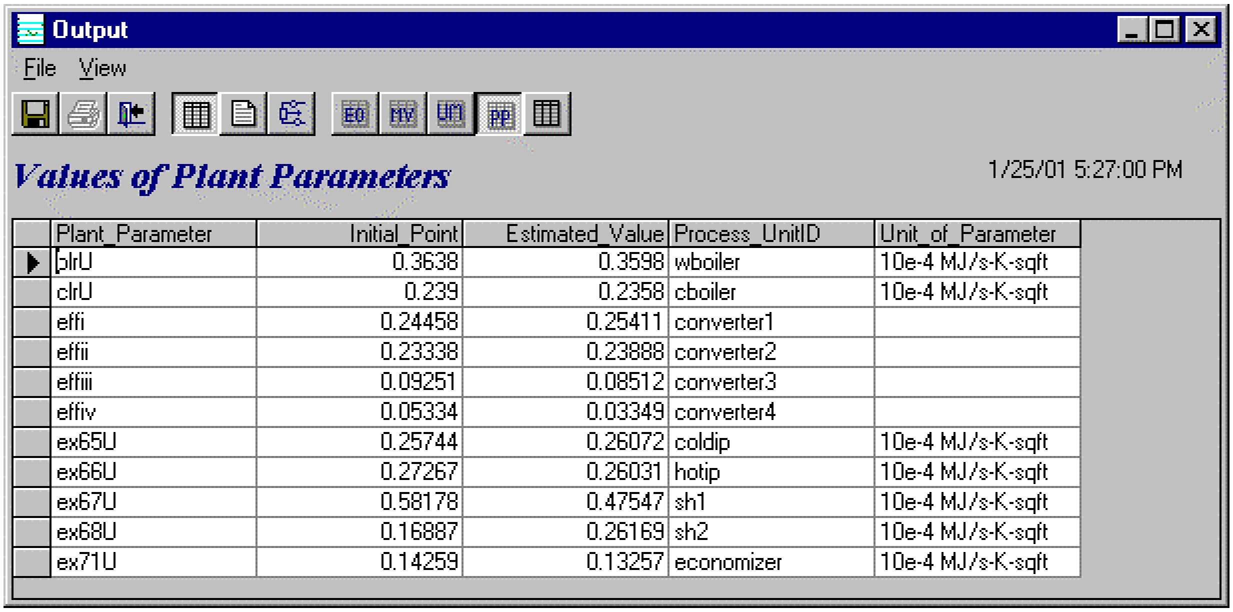


Values of Measured Variables

1/25/01 5:27:00 PM

Name	Optimal_Set_Point	Reconciled_Data_From_Parameter_Estimation	Reconciled_Data_From_
F06	2.20773	2.18251	
f50	0.24405	0.24072	
fsbfw	1.95	1.91	
O2percent	5.31276	5.3484	
Pshp1	700	614.7	
Pshp2	700	614.7	
Pss2	712.51882	709.7	
SO2ppm	380	219.56088	
T06	355	359.18972	
T07	1321.84558	1322.41247	
T09	650	646.48333	
T10	712.6556	710.2611	
T11	892.21502	890.99131	
T12	692.21161	690.76099	
T13	784.06521	781.89845	
T15	505	504.69012	
T16	345	347.2783	
T19	548.24266	549.26111	
T20	695	694.73609	

Figure 48: Optimal Set points and Reconciled Data in Final Report for Measured Variables

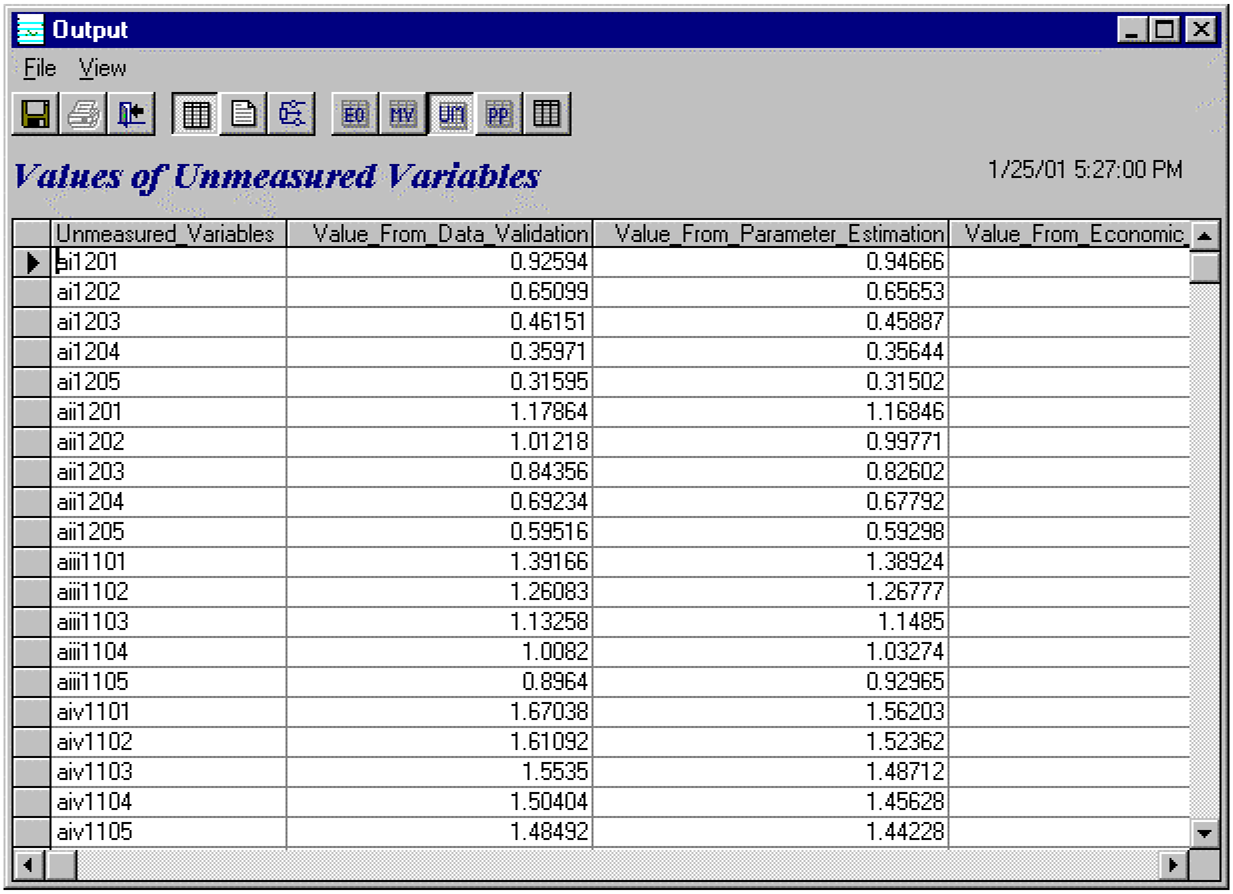


Values of Plant Parameters

1/25/01 5:27:00 PM

Plant_Parameter	Initial_Point	Estimated_Value	Process_UnitID	Unit_of_Parameter
blrU	0.3638	0.3598	wboiler	10e-4 MJ/s-K-sqft
clrU	0.239	0.2358	cboiler	10e-4 MJ/s-K-sqft
effi	0.24458	0.25411	converter1	
effii	0.23338	0.23888	converter2	
effiii	0.09251	0.08512	converter3	
effiv	0.05334	0.03349	converter4	
ex65U	0.25744	0.26072	coldip	10e-4 MJ/s-K-sqft
ex66U	0.27267	0.26031	hotip	10e-4 MJ/s-K-sqft
ex67U	0.58178	0.47547	sh1	10e-4 MJ/s-K-sqft
ex68U	0.16887	0.26169	sh2	10e-4 MJ/s-K-sqft
ex71U	0.14259	0.13257	economizer	10e-4 MJ/s-K-sqft

Figure 49: Estimated Values of Plant Parameters in Final Report



Values of Unmeasured Variables

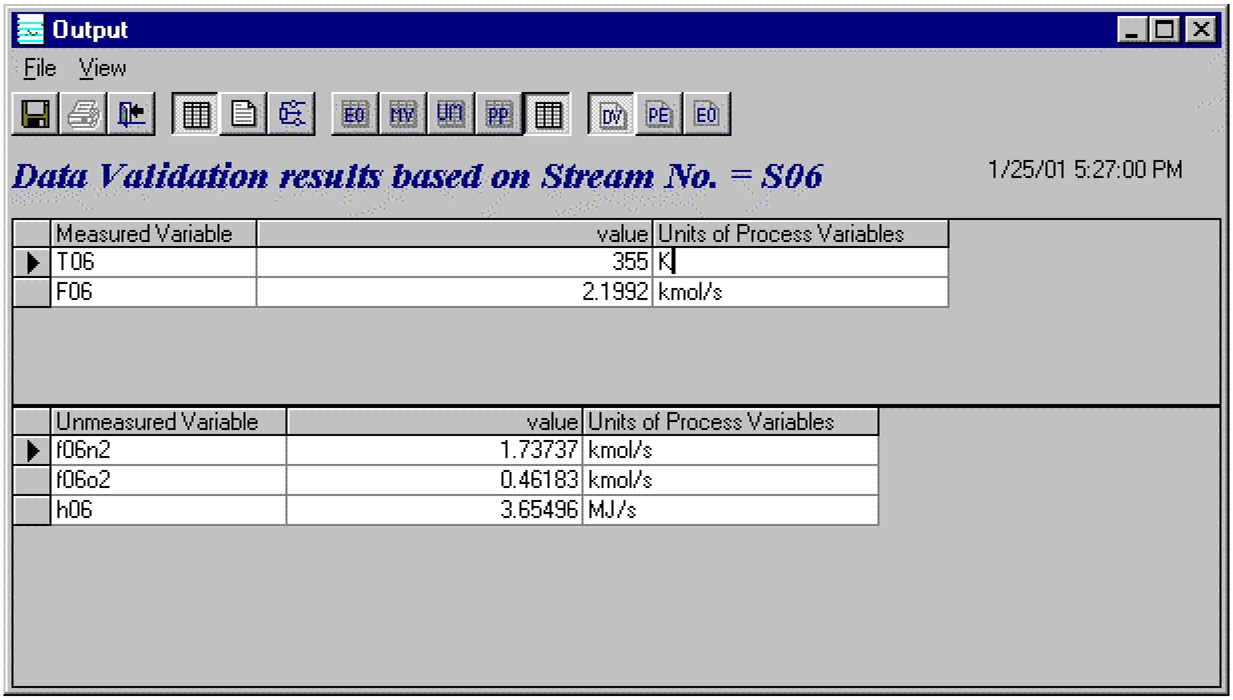
1/25/01 5:27:00 PM

Unmeasured_Variables	Value_From_Data_Validation	Value_From_Parameter_Estimation	Value_From_Economic_
ai1201	0.92594	0.94666	
ai1202	0.65099	0.65653	
ai1203	0.46151	0.45887	
ai1204	0.35971	0.35644	
ai1205	0.31595	0.31502	
aii1201	1.17864	1.16846	
aii1202	1.01218	0.99771	
aii1203	0.84356	0.82602	
aii1204	0.69234	0.67792	
aii1205	0.59516	0.59298	
aiii1101	1.39166	1.38924	
aiii1102	1.26083	1.26777	
aiii1103	1.13258	1.1485	
aiii1104	1.0082	1.03274	
aiii1105	0.8964	0.92965	
aiv1101	1.67038	1.56203	
aiv1102	1.61092	1.52362	
aiv1103	1.5535	1.48712	
aiv1104	1.50404	1.45628	
aiv1105	1.48492	1.44228	

Figure 50: Reconciled Values for Unmeasured Variables

Clicking on the “Unmeasured Variables”, the system opens a spreadsheet data form which includes the unmeasured variables and their reconciled values as shown in Figure 50

Three options are available in the ‘Stream Number’ menu as shown in Figure 47. The three options are Data from Data Validation, Data from Parameter Estimation and Optimal Setpoints. Let us click the ‘Data from Data Validation’ option. An input box appears. Let us enter ‘s06’ and click ‘Ok’. The Measured Variables and Unmeasured variables which are associated with the stream ‘s06’ with their reconciled values from Data Validation are displayed as shown in Figure 51.



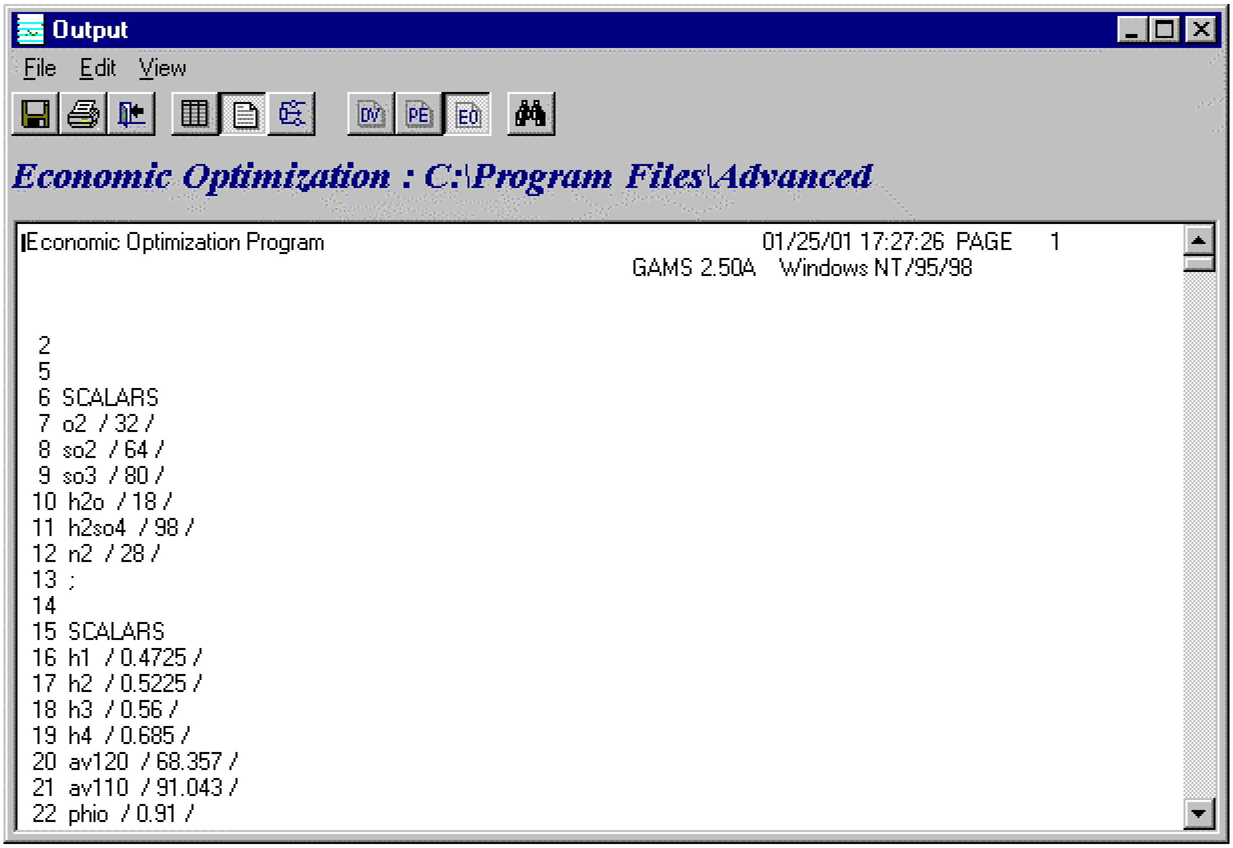
Data Validation results based on Stream No. = S06

1/25/01 5:27:00 PM

Measured Variable	value	Units of Process Variables
T06	355	K
F06	2.1992	kmol/s

Unmeasured Variable	value	Units of Process Variables
f06n2	1.73737	kmol/s
f06o2	0.46183	kmol/s
h06	3.65496	MJ/s

Figure 51: Information based on Stream Number



```
Economic Optimization Program                                01/25/01 17:27:26  PAGE     1
                                                      GAMS 2.50A   Windows NT/95/98

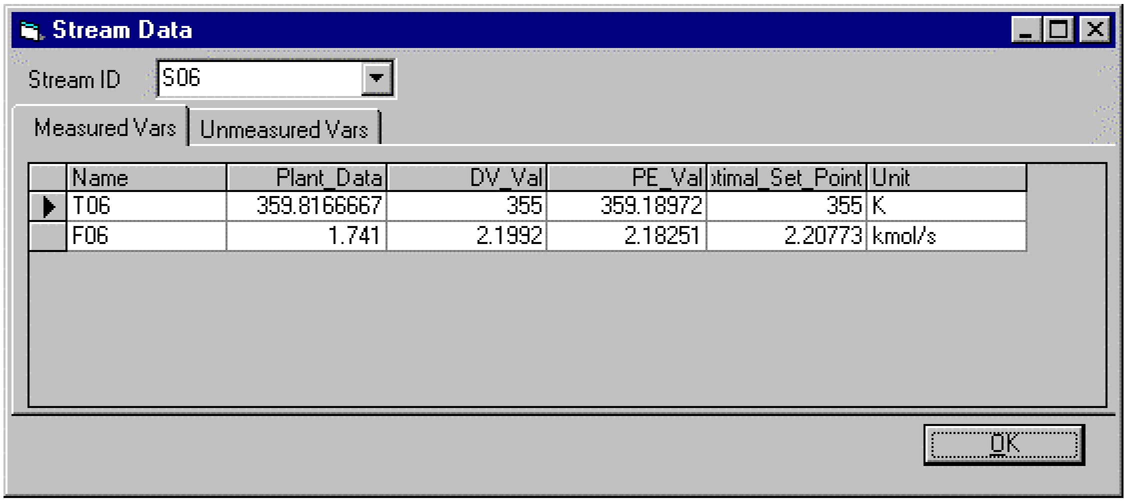

  2
  5
  6  SCALARS
  7  o2  / 32 /
  8  so2  / 64 /
  9  so3  / 80 /
 10  h2o  / 18 /
 11  h2so4  / 98 /
 12  n2  / 28 /
 13  ;
 14
 15  SCALARS
 16  h1  / 0.4725 /
 17  h2  / 0.5225 /
 18  h3  / 0.56 /
 19  h4  / 0.685 /
 20  av120  / 68.357 /
 21  av110  / 91.043 /
 22  phio  / 0.91 /
```

Figure 52 Full Output File of GAMS Programs

When the ‘Full Output file’ option in the view menu is selected, three buttons are displayed in the toolbar each corresponding to the three optimization problems. Clicking a button will open the corresponding output file for viewing. Let us click on ‘Economic Optimization’ option in the Full output menu. The front part of full output file is shown in Figure 52 and the entire file is shown in Appendix B.

The user can use the ‘Find’ and ‘Goto’ options in the Edit menu to search for a particular phrase or go to a particular section in the Full output file.The Final Report can be exported as Excel files using the ‘Export’ option in the file menu. The Full Output files can also be exported as text files using the ‘Export’ option.

Flowsheet can be viewed in results , in a window similar to the one shown in Figure 42. Double clicking on a stream or unit opens the corresponding data window. The Data window for stream ‘s06’ is shown in Figure 53. As seen in this figure, the values of the measured variables obtained as a result of on-line optimization are displayed in the data window.



Stream ID: S06

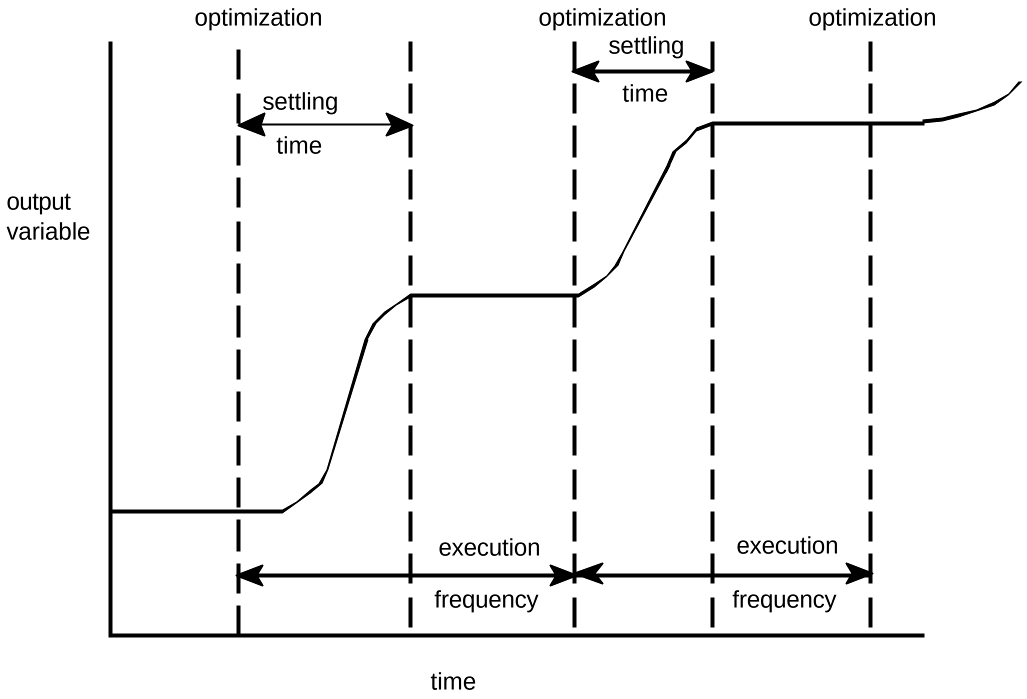
Name	Plant_Data	DV_Val	PE_Val	timal_Set_Point	Unit
T06	359.8166667	355	359.18972	355	K
F06	1.741	2.1992	2.18251	2.20773	kmol/s

Figure 53: Stream Data Window

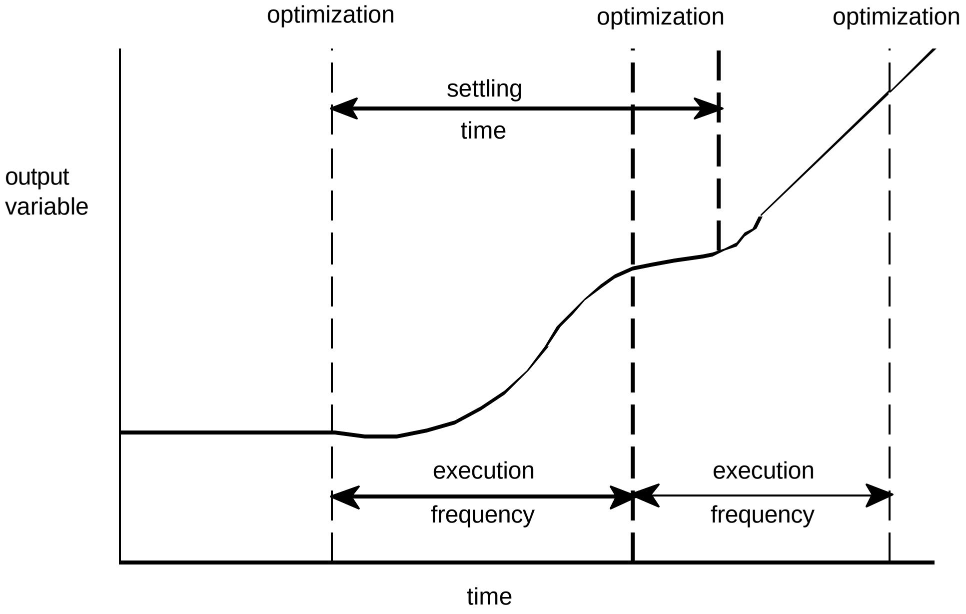
Clicking the ‘Close’ option in the file menu of the Output window returns the user to the main screen, which was shown in Figure 34. The model information can be exported as Excel files using the ‘Export’ option in the file menu of the main window. Save the optimization results using the ‘Save’ option in the file menu. The results including the full output files are stored along with the Contact model. When the ‘Exit’ button is clicked, the Interactive On-line Optimization main window is closed and the user is taken back to the Advanced Process Analysis Desk.

Steady-State Detection and Execution Frequency

On-line optimization executes economic optimization and generates a set of optimal set point. Then these set points are transferred to the coordinator program or the operators as an Excel spreadsheet file. These optimal set points can be sent directly to distributed control system or they can be viewed by operators before they are sent to the DCS. Before the optimal set points are implemented, the steady state detection program is run to ensure the process is at steady state. The following gives detailed information about steady-state detection and execution frequency.



a. Time between optimizations is longer than settling time



b. Time between optimizations is less than settling time

Figure 54 Comparison of Time between Optimizations and Process Settling Time after Darby and White (1988).

The execution frequency for optimization is the time between conducting on-line optimization of the process, and it has to be determined for each of the units in the process. It depends on the settling time, i.e., the time required for the units in the process to move from one set of steady-state operating condition to another. This settling time can be estimated from the time constant determined by process step testing. The time period between two on-line optimization executions must be longer than the settling time to ensure that the units have returned to steady state operations before the optimization is conducted again. This is illustrated in Figure 54, after Darby and White (1988). The figure shows that execution frequency for optimization in Figure 55a was satisfactory for the process but the execution frequency in Figure 54b was too rapid for the process. In Figure 54a, the process has returned to steady-state operations and held that position until the next optimization. However, in Figure 54b, the process did not have enough time to return to steady-state operations before the optimization altered the operating conditions. The process would continue on an unsteady state path, and operator intervention would be required. The settling time for an ethylene plant is four hours according to Darby and White (1988), and this time for the sulfuric acid contact process is twelve-hour according Hertwig (1997).

As shown in Figure 55, it is necessary to make sure that the process is operating at steady state before the plant data is taken from distributed control system for conducting on-line optimization. Steady state plant data is required for steady state process models.

The time series horizontal screening method has been used in industry to detect steady state. In this method, the measured values for key process variables are observed for a time period. If the measured values remain within the bounds of two standard deviations, then the process is said to be operating at steady state. This requires the use of a coordinator program or operator action for identifying steady state and exchanging data between the on-line optimization program and the distributed control system. Excel spreadsheet files are widely used to transfer the data. The use of an Excel spreadsheet is the industry standard way of selecting data and manipulating data from a DCS. Steady state detection and data exchange will be illustrated with plant data for the contact process.

As shown in Figure 55 on-line optimization executes economic optimization and generates a set of optimal set point. Then these set points are transferred to the coordinator program or the operators as an Excel spreadsheet file. These optimal set points can be sent directly to distributed control system or they can be viewed by operators before they are sent to the DCS. Before the optimal set points are implemented, the steady state detection program is run to ensure the process is at steady state.

To incorporate the capability for steady state detection, an Excel worksheet program was prepared, *steady_state.xls,* and it is included in the files with the on-line optimization program. The contact process is used to illustrate the use of this program for time series analysis for steady state detection. The first sheet in the Excel program has 20 sets of plant data obtained for the contact process. This information is shown in Figure 56 for the first 14 of these data sets, and each column represents data for the 29 measured variables that would be taken from the data historian of the distributed control system for 20 time intervals ending with the current time.

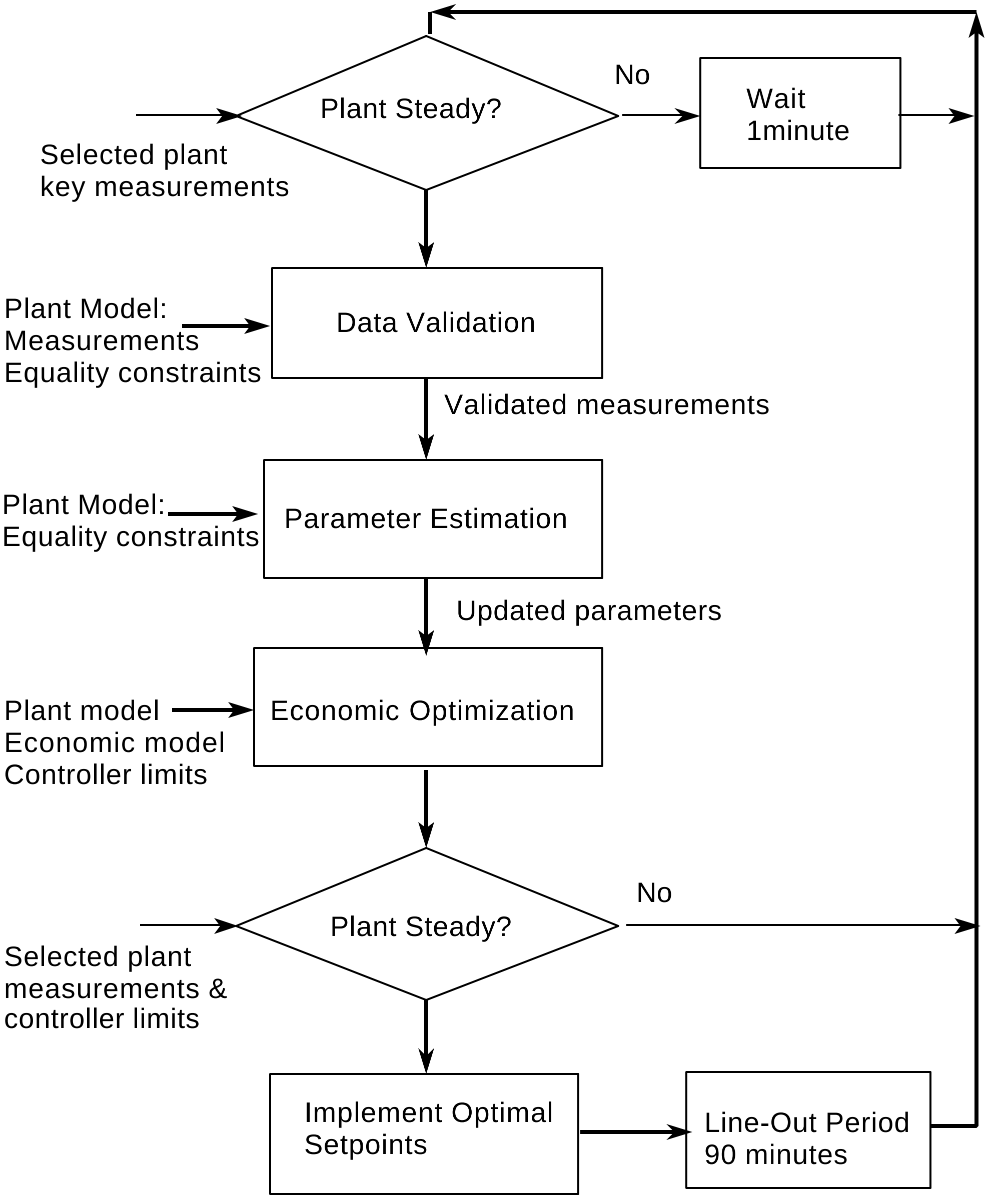


Figure 55 Implementation Procedure for On-Line Optimization, after Kelly, et al. (1996)

The second Excel spreadsheet was prepared to analyze this data to determine a time interval that shows the plant is operating at steady state. This spreadsheet is shown in Figure 57, and the graphs and buttons were developed using the Visual Basic capabilities that are part of Excel. In this figure the time series of four of the measured variables can be viewed at one time. The spreadsheet has the capability of displaying any four of the process variables, and the variables that are plotted can be changed by pulling down the menu on the lower left and selecting a variable to be displayed.

After reviewing the data in Figure 57, it was determined that the plant was at steady state between time periods 3 and 5. These times correspond to 11 a.m. and 7 p.m. on February 3,

1998. Consequently, the decision is to import the data from 3 p.m., into the on-line optimization program. On this diagram, the Save Steady State Data button is clicked and the program has the user designate the time interval of the data which is saved to the third spreadsheet, a single column of data that is not shown here as a figure.

The user is now ready to transfer this steady state data to the on-line optimization program. Return to the Declaration Window for Measured Variables, which is shown in Figure 37 and pull down the File menu. This is shown in Figure 58 and then select Import Plant Data. This action brings up the window shown in Figure 59, and in this window the name of the Excel file is designated which contains the steady state plant data that was selected with the Excel time series program. Clicking the Open button will replace the plant data currently in the program. Now having the new data in place, the on-line optimization program can be executed to generate the new set of optimal points for the distributed control system.

The execution of the on-line optimization program generates the set points for the distributed control system. These values can be exported from the on-line optimization program using the same procedure as importing data. The file menu in these windows has a line Export Plant Data which, when clicked, gives a screen similar to the one in Figure 59 to specify the Excel file to transfer this data. The on-line optimization program requires the standard deviation of the measured variables as shown in Figure 37. The Excel program *steady_state.xls* is used also to calculate the standard deviation of the measured variables. Although not shown in Figure 56, the last column in the spreadsheet is the standard deviation of the measured variables, which was calculated using the 20 measurements. This information can be transferred to the on-line optimization program using the same procedure as was used for the measured variables. However, it is not necessary to use the current plant data to evaluate the standard deviation, and the Excel program can be used with any data set to determine appropriate values of the standard deviation.

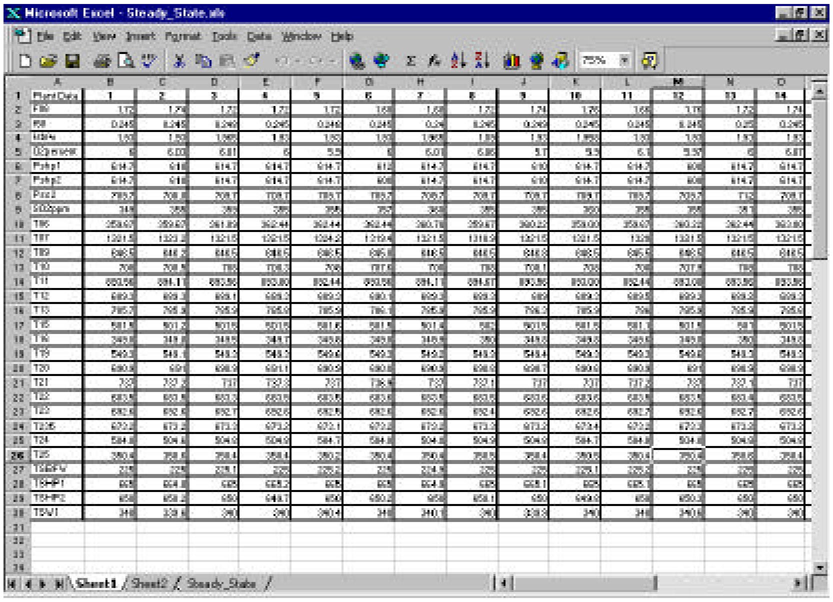


Figure 56 Excel Spreadsheet of Plant Data for the Contact Process

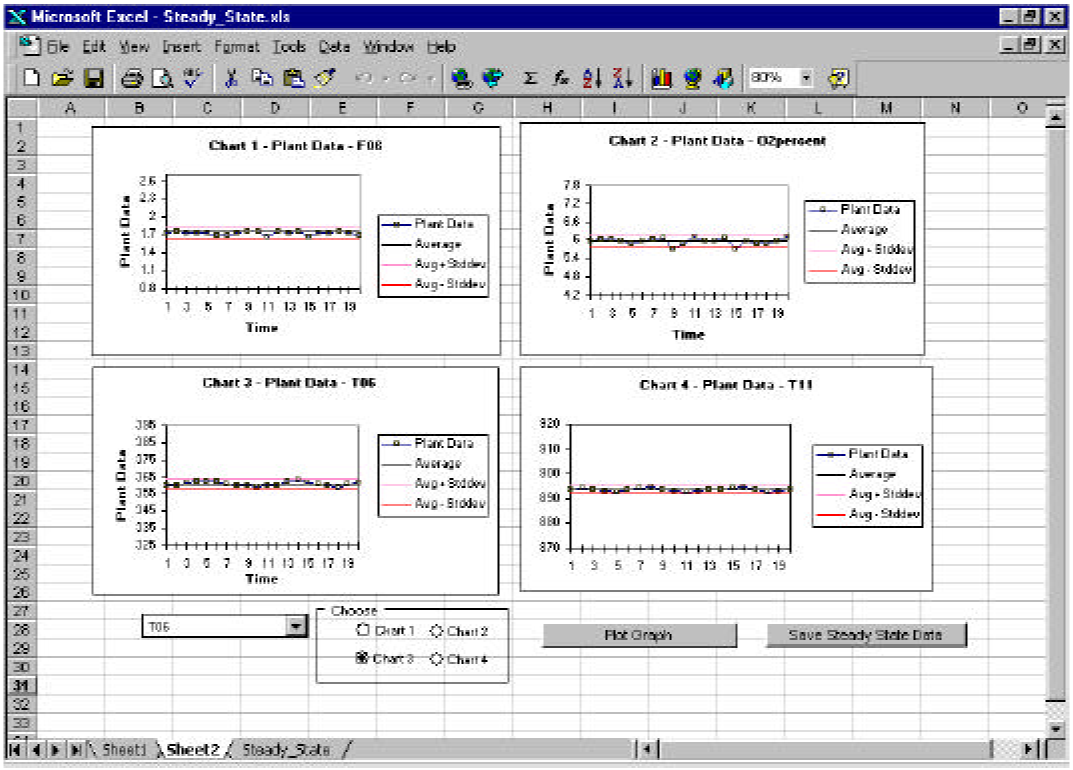
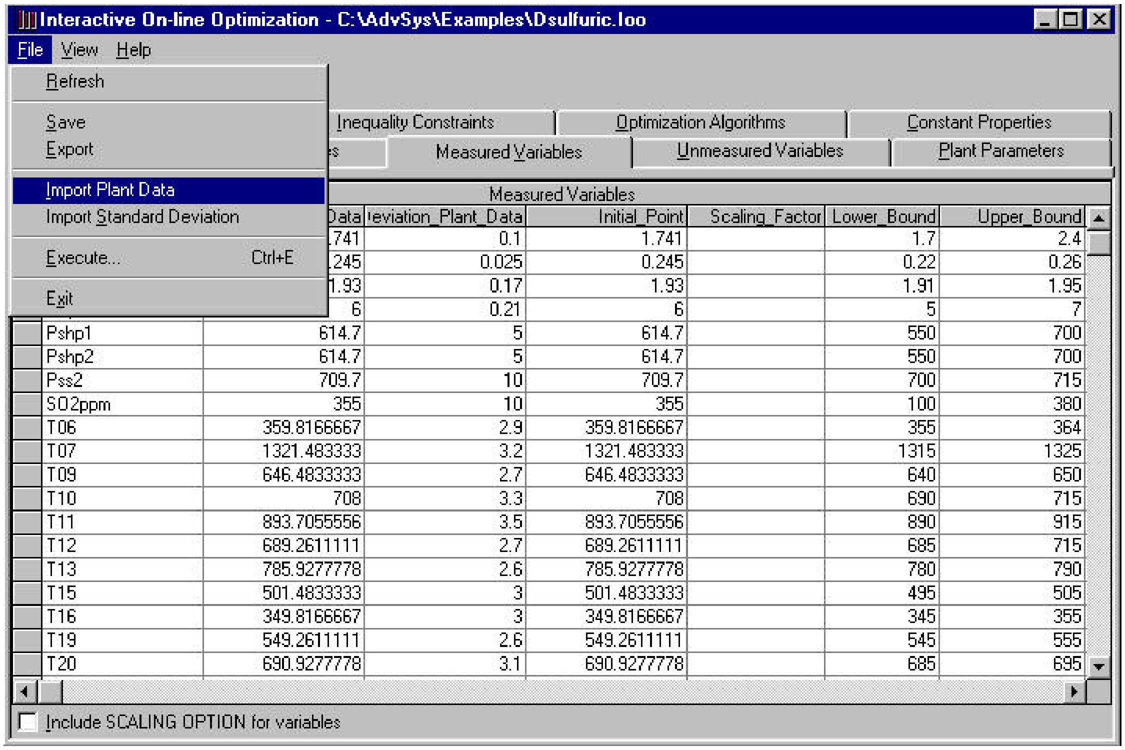


Figure 57 Excel Spreadsheet Showing the Time Series Graphs of the Data

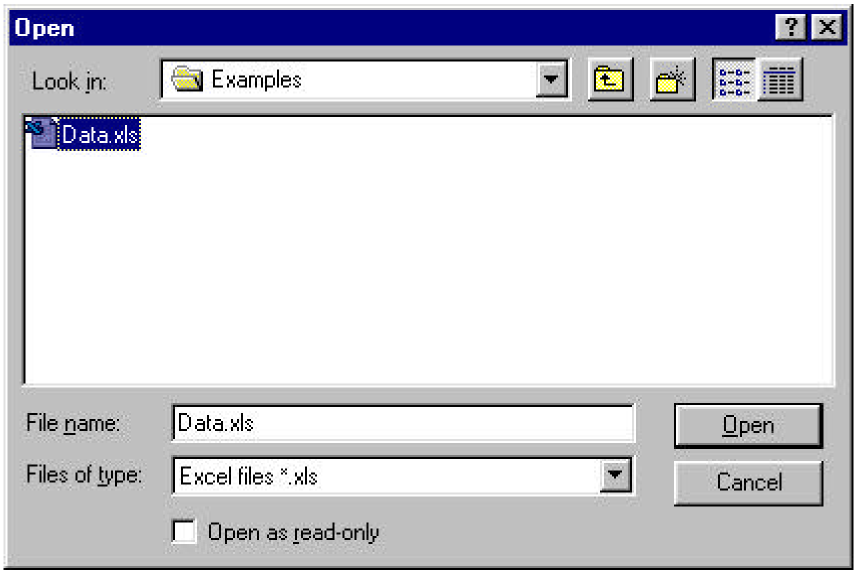


Measured Variables

	Data	eviation_Plant_Data	Initial_Point	Scaling_Factor	Lower_Bound	Upper_Bound
	.741	0.1	1.741		1.7	2.4
	.245	0.025	0.245		0.22	0.26
	1.93	0.17	1.93		1.91	1.95
	6	0.21	6		5	7
Pshp1	614.7	5	614.7		550	700
Pshp2	614.7	5	614.7		550	700
Pss2	709.7	10	709.7		700	715
SO2ppm	355	10	355		100	380
T06	359.8166667	2.9	359.8166667		355	364
T07	1321.483333	3.2	1321.483333		1315	1325
T09	646.4833333	2.7	646.4833333		640	650
T10	708	3.3	708		690	715
T11	893.7055556	3.5	893.7055556		890	915
T12	689.2611111	2.7	689.2611111		685	715
T13	785.9277778	2.6	785.9277778		780	790
T15	501.4833333	3	501.4833333		495	505
T16	349.8166667	3	349.8166667		345	355
T19	549.2611111	2.6	549.2611111		545	555
T20	690.9277778	3.1	690.9277778		685	695

☐ Include SCALING OPTION for variables

Figure 58 The Import Option in the File menu of On-line Optimization



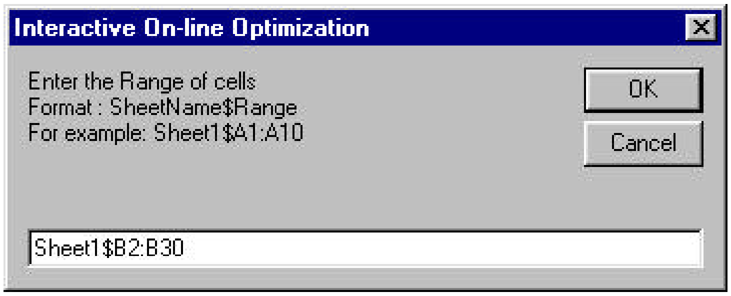
Look in: Examples

Data.xls

File name: Data.xls

Files of type: Excel files *.xls

Figure 59 The Dialog Box that opens when Import is clicked



Enter the Range of cells
Format : SheetName$Range
For example: Sheet1$A1:A10

Sheet1$B2:B30

Figure 60 The Screen to enter the Excel Sheet Name and Range

This concludes the description of steady-state detection and execution frequency of on-line optimization. The next step of Advanced Process Analysis System is the heat exchanger network optimization. Click the ‘Pinch Analysis’ button in Advanced Process Analysis Desk to open the heat exchanger network (THEN) program.

VII. USING THE HEAT EXCHANGER NETWORK (THEN) PROGRAM

Upon clicking the ‘Pinch Analysis’ button on the Advanced Process Analysis Desk, the ‘Heat Exchanger Network Model Information’ window is displayed. This window is shown in Figure 61. Since we are using the THEN program for the first time, click the ‘New Model’ button.

Once the ‘New Model’ button is clicked, the ‘Welcome Screen’ of the Heat Exchanger Network program is displayed. This screen is shown in Figure 62. The message at the center confirms that you are working on the process model ‘Dsulfuric.ioo’ in the ‘Examples’

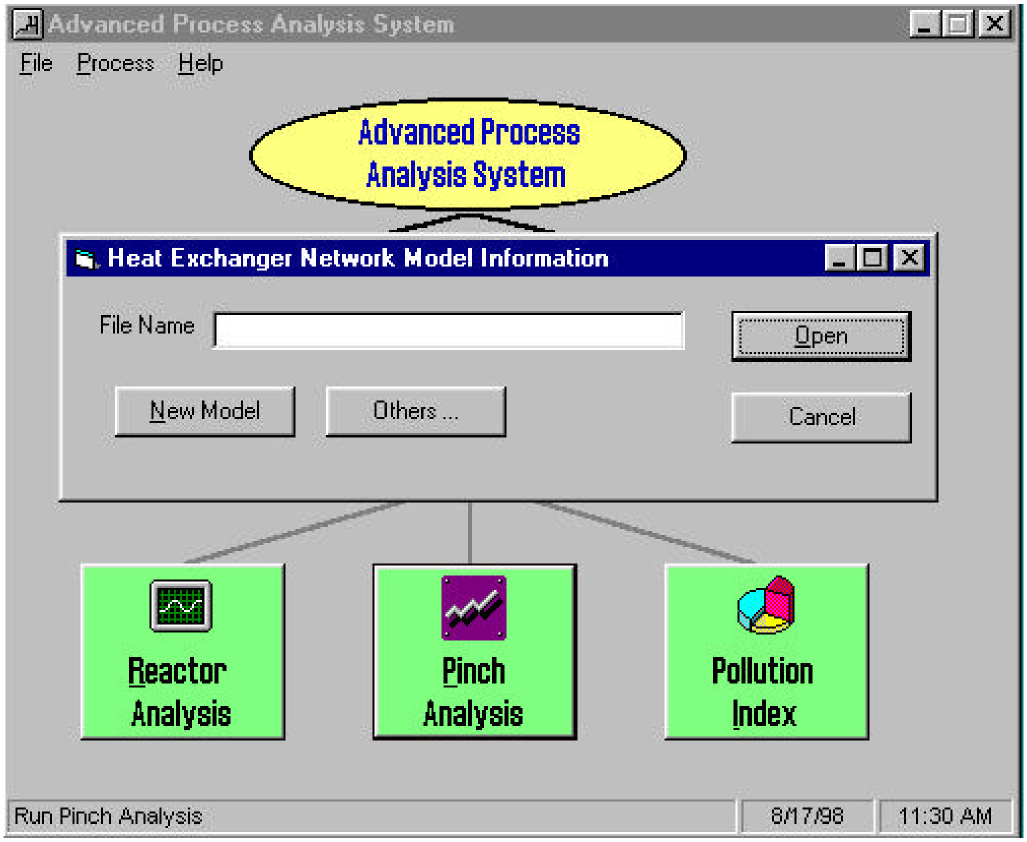
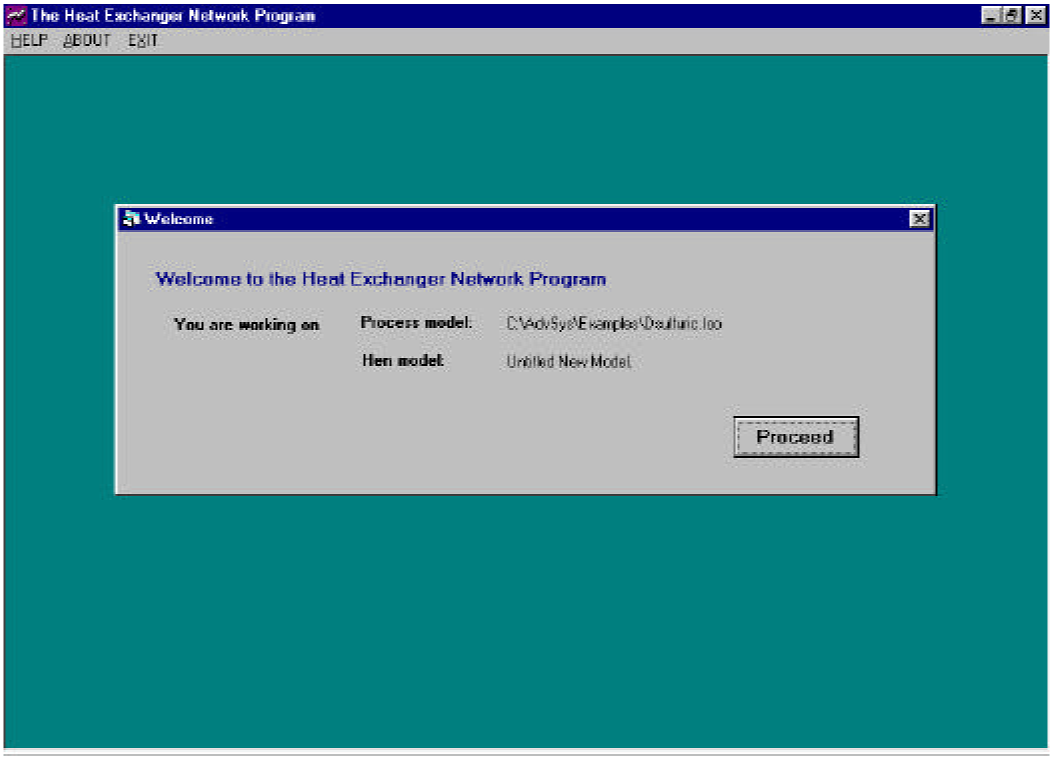


Figure 61 The Heat Exchanger Network Model Information Window

subdirectory. The HEN model you are working on is an untitled new model. A HEN model is an input file created by the heat exchanger network program to apply pinch analysis to the process model. A HEN model is stored as a file with 'hen' extension (e.g. sample.hen).

The menu at the top of the background window is the 'main menu' of THEN. It is available at all times during the execution of the program. The 'Help' button can be used to access online help. The 'About' button gives the copyright information. The 'Exit' button can be used to quit the program at any time and go back to the Advanced Process Analysis Desk.

Click on the 'Proceed' button on the welcome screen. The 'Stream List' window is now displayed on the screen. This is shown in Figure 63. The box in the center shows the list of all the process streams and their descriptions. This list has been automatically retrieved by the program based on the information in the flowsheet diagram. Scroll up and down in the box to see the entire list. There is a check box available to the left of each stream name in the list. If a process stream is important for heat integration, the check box for that stream needs to be selected. For the Contact model, the following streams are determined to be important; s08, s09, s11, s12, s13, s15, s16, s20, s21, s22, s23, s24. Select all of these streams in the list by clicking on their checkboxes.



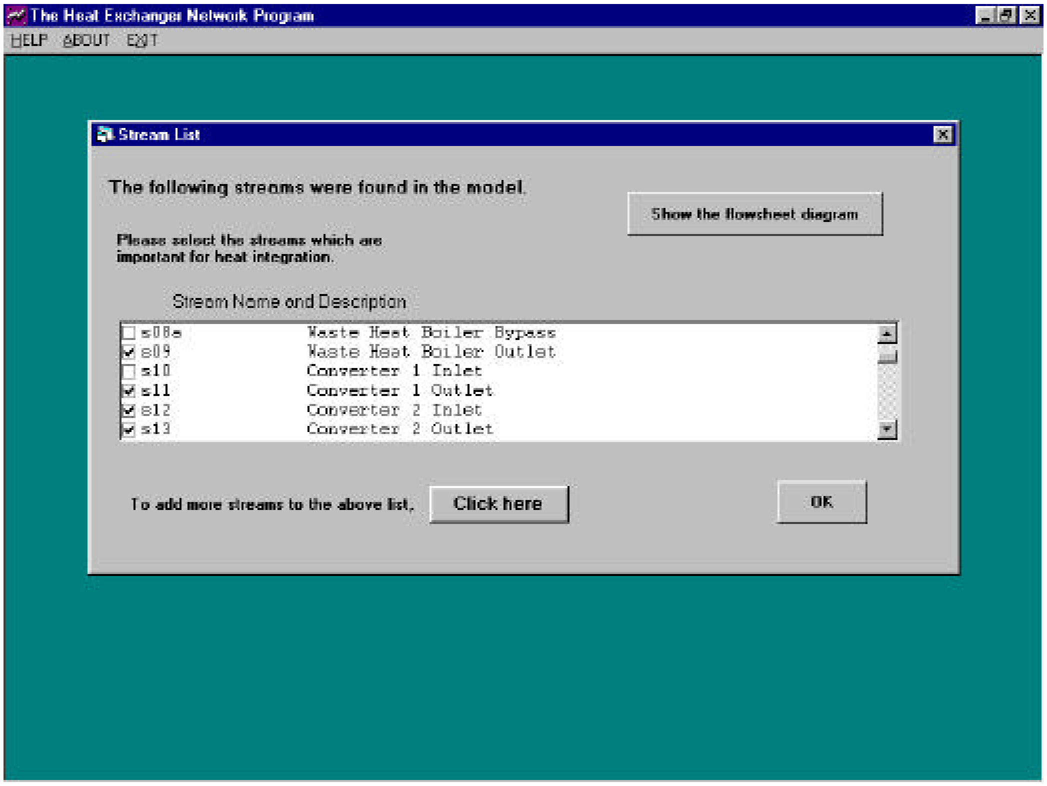
Welcome to the Heat Exchanger Network Program

You are working on

Process model: C:\AdvSys\Examples\Dsulfuric.loo

Hen model: Untitled New Model

Figure 62 The Welcome Screen of THEN



The following streams were found in the model.

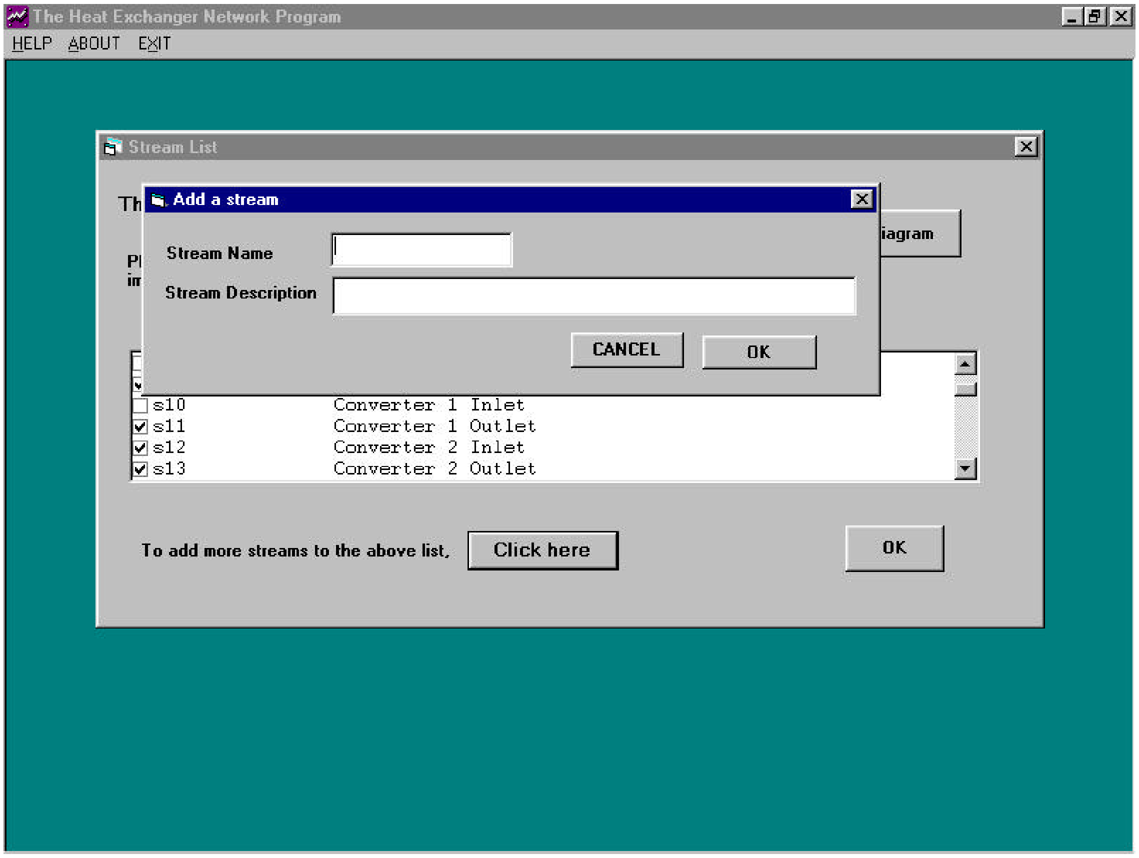
Please select the streams which are important for heat integration.

Stream Name and Description

☐ s08a	Waste Heat Boiler Bypass
☑ s09	Waste Heat Boiler Outlet
☐ s10	Converter 1 Inlet
☑ s11	Converter 1 Outlet
☑ s12	Converter 2 Inlet
☑ s13	Converter 2 Outlet

To add more streams to the above list,

Figure 63 The Stream List Window



```
☐ s10    Converter 1 Inlet
☑ s11    Converter 1 Outlet
☑ s12    Converter 2 Inlet
☑ s13    Converter 2 Outlet
```

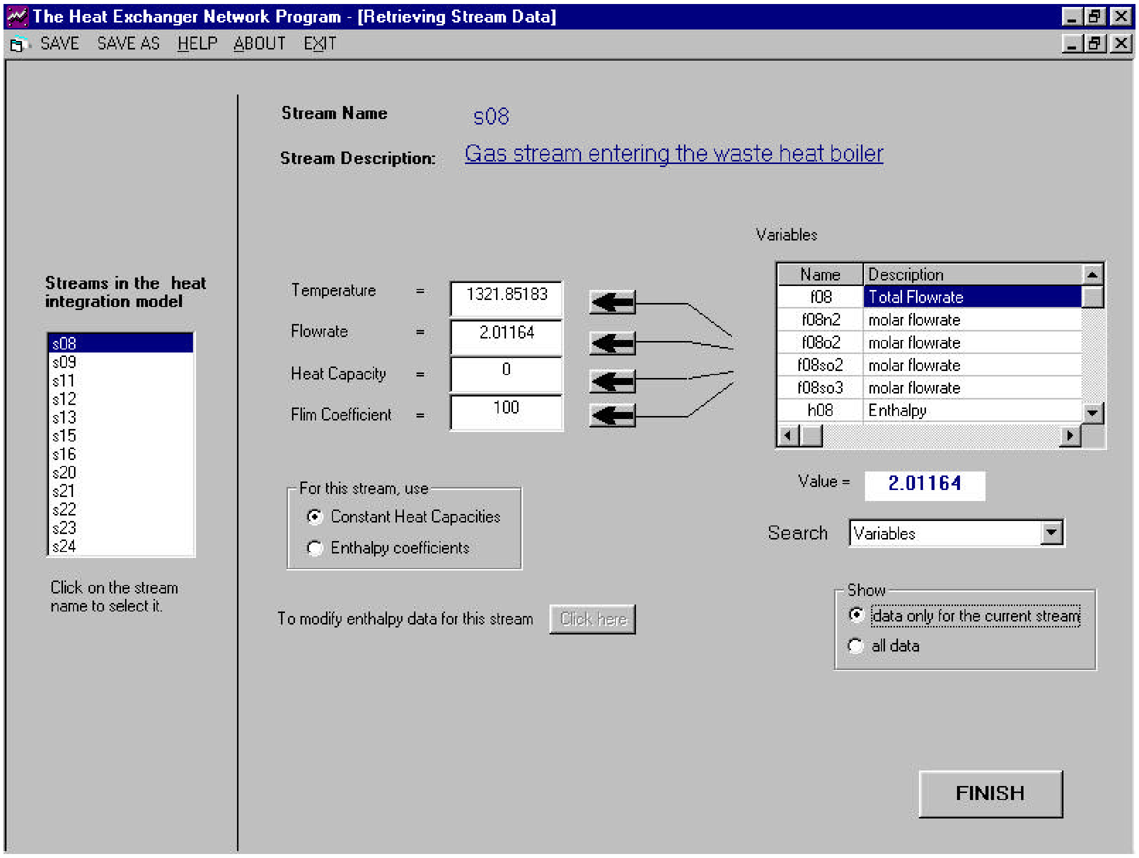
To add more streams to the above list,

Figure 64 The Add Stream Window

The button ‘Show the flowsheet diagram’ at the top of the stream list window can be used to view the flowsheet diagram at any time. In addition to the streams listed, new streams can also be added. To add a stream, click the ‘Click here’ button at the bottom of the window. A small window shown in Figure 64 is displayed. A stream name and a description must be entered. Clicking the ‘OK’ button will add the stream to the list. For the Contact model, we do not want to add any stream. So, click the ‘Cancel’ button to go back to the ‘Stream List’ window.

Having selected all the important streams in the Stream List window, click the ‘OK’ button to continue. The next window displayed on the screen is the ‘Retrieving Stream Data’ window shown in Figure 65. A vertical line divides this window into two parts. The left side of the screen displays a list. This list contains all the streams, which were selected earlier in the ‘Stream List’ window. As can be seen from the Figure 65, all the twelve streams that were chosen as the important streams are present in the list.

The heat exchanger network program needs certain information for each stream in order to apply pinch analysis. This information includes temperature, flowrate, enthalpies and film heat transfer coefficient. The values of all of these variables have to be retrieved for each of the selected streams. The values for temperature and flowrate are automatically retrieved by the



Stream Name s08

Stream Description: Gas stream entering the waste heat boiler

Streams in the heat integration model:
- s08
- s09
- s11
- s12
- s13
- s15
- s16
- s20
- s21
- s22
- s23
- s24

Temperature = 1321.85183

Flowrate = 2.01164

Heat Capacity = 0

Flim Coefficient = 100

Name	Description
f08	Total Flowrate
f08n2	molar flowrate
f08o2	molar flowrate
f08so2	molar flowrate
f08so3	molar flowrate
h08	Enthalpy

Value = 2.01164

Search: Variables

For this stream, use
- ● Constant Heat Capacities
- ○ Enthalpy coefficients

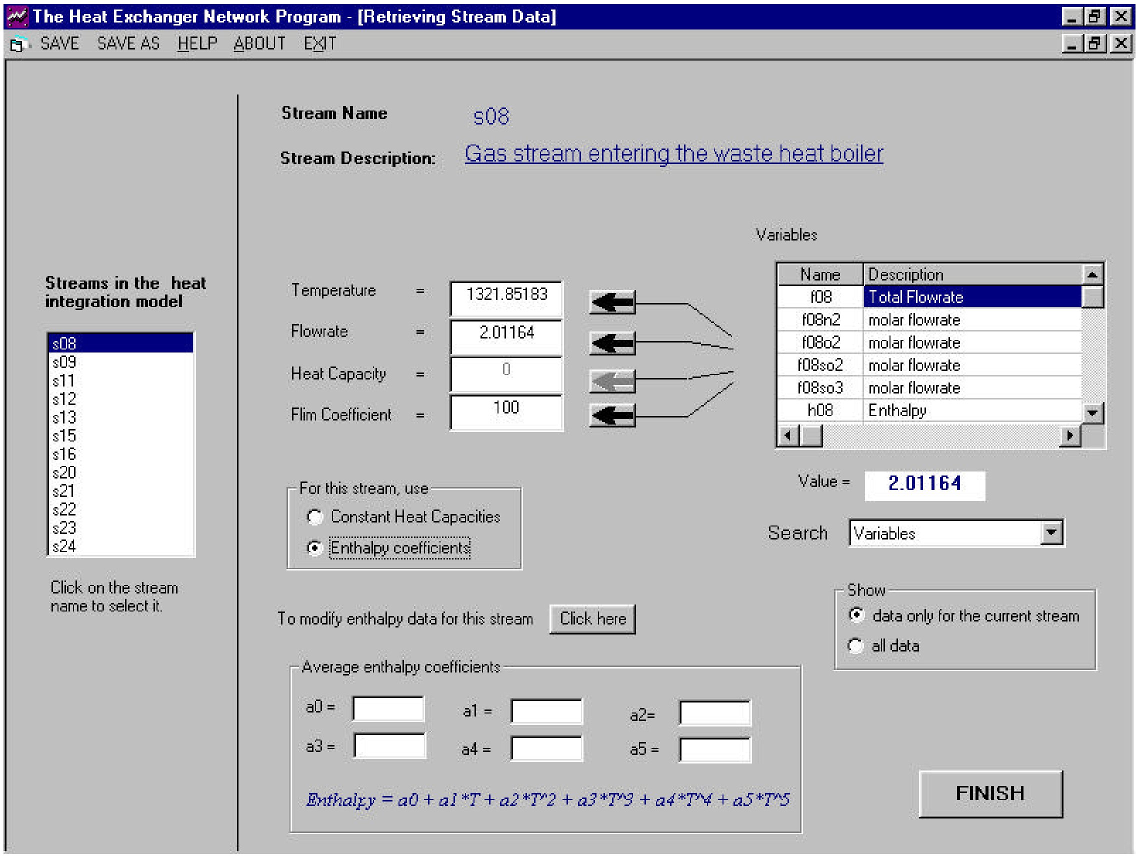
Show
- ● data only for the current stream
- ○ all data

Figure 65 The Retrieving Stream Data Window

program from the results of economic optimization carried out earlier during Advanced Process Analysis System. The values for enthalpies and film heat transfer coefficients have to be entered by the user. To understand how the data is retrieved, let us enter the data for the stream s08.

Click on the stream s08 in the list on the left side of the screen. On the right side of the screen, the stream name and stream description labels now show ‘s08’ and ‘Gas stream entering the waste heat boiler’ respectively. As can be seen in Figure 65, the temperatures and flowrate values for stream s08 have been automatically retrieved and displayed. The heat capacity and film coefficient values are initialized to the defaults, which are 0 and 100 respectively.

The enthalpy data for any stream can be entered as either constant heat capacity coefficients or temperature-dependent enthalpy coefficients. The variation in temperature is large for the streams in the Contact model. So, the temperature-dependent enthalpy coefficients are used for all the streams. To enter these coefficients for stream s08, select the ‘enthalpy coefficients’ option. Once this option is selected, the button for modifying enthalpy data becomes enabled and a small frame for the average enthalpy coefficients of stream s08 can now be seen. This view is shown in Figure 66. The frame also shows the enthalpy formula used in the program.



Stream Name s08

Stream Description: Gas stream entering the waste heat boiler

Temperature = 1321.85183

Flowrate = 2.01164

Heat Capacity = 0

Flim Coefficient = 100

Variables

Name	Description
f08	Total Flowrate
f08n2	molar flowrate
f08o2	molar flowrate
f08so2	molar flowrate
f08so3	molar flowrate
h08	Enthalpy

Value = 2.01164

Search: Variables

For this stream, use
○ Constant Heat Capacities
● Enthalpy coefficients

Show
● data only for the current stream
○ all data

To modify enthalpy data for this stream

Average enthalpy coefficients

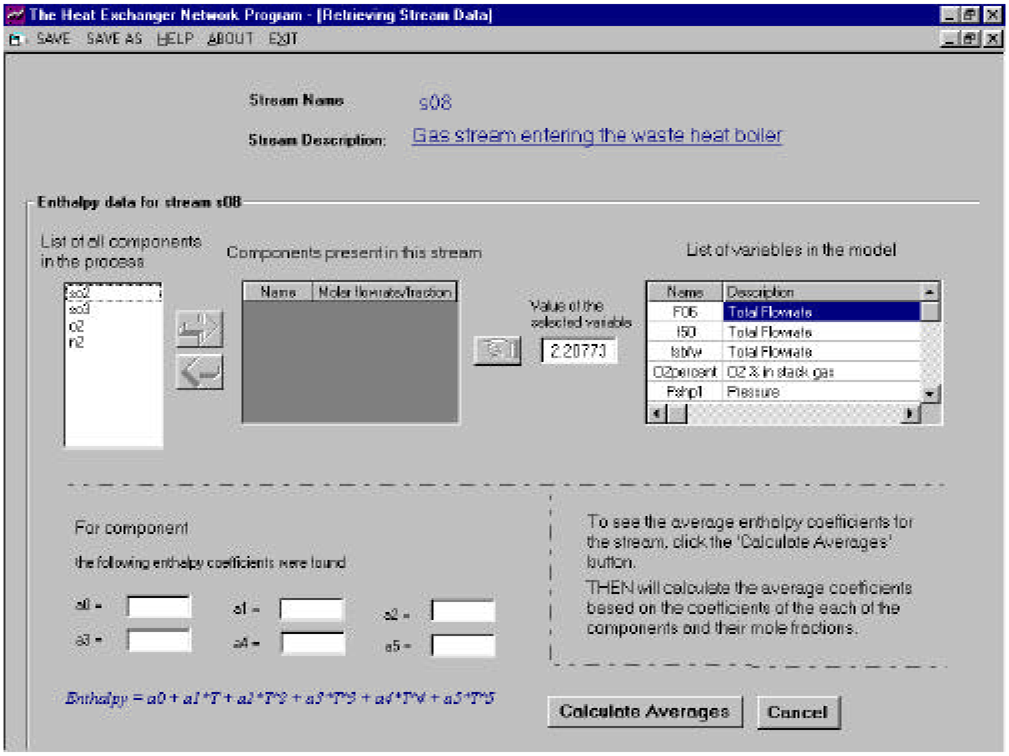
a0 =
a1 =
a2=
a3 =
a4 =
a5 =

$Enthalpy = a0 + a1*T + a2*T^2 + a3*T^3 + a4*T^4 + a5*T^5$

Figure 66 The Retrieving Stream Data Window with the Average Enthalpy Coefficients

If the average enthalpy coefficient values are known for the stream, they can be entered in the corresponding boxes in the frame. Since, we do not know the average values, we will calculate them from the stream composition and the enthalpy coefficient values for the individual chemical species present in that stream. To perform these calculations, click the button for modifying the enthalpy data. When this button is clicked, the screen view changes to the ‘Enthalpy Data’ window shown in Figure 67.

The ‘Enthalpy Data’ window shows a list of all the chemical components present in the process. The components present in the reacting gases in Contact model are O_2, N_2, SO_2, and SO3. These are automatically retrieved from Flowsim and displayed in the enthalpy data window. The table ‘Components present in this stream’ shows the components, which are present in stream s08. This table is empty as seen in Figure 67. This is because the components present in a stream need to be manually selected by the user and added to the table. From our knowledge about the process, we know that stream s08 has all four of the above listed components. So, let us add all of these components to the table. Click on the component name in list. The button with an arrow pointing towards the table now becomes enabled. Click on this button and the component gets transferred from the list to the table. After repeating this for all four components, the screen looks as shown in Figure 68. The table ‘Components present in this stream’ now has all four components and the list is empty.



Stream Name s08

Stream Description: Gas stream entering the waste heat boiler

Enthalpy data for stream s08

List of all components in the process

so2
so3
o2
n2

Components present in this stream

Name	Molar flowrate/fraction

Value of the selected variable 2.20773

List of variables in the model

Name	Description
F06	Total Flowrate
I50	Total Flowrate
lsbfw	Total Flowrate
O2percent	O2 % in stack gas
Pshp1	Pressure

For component

the following enthalpy coefficients were found

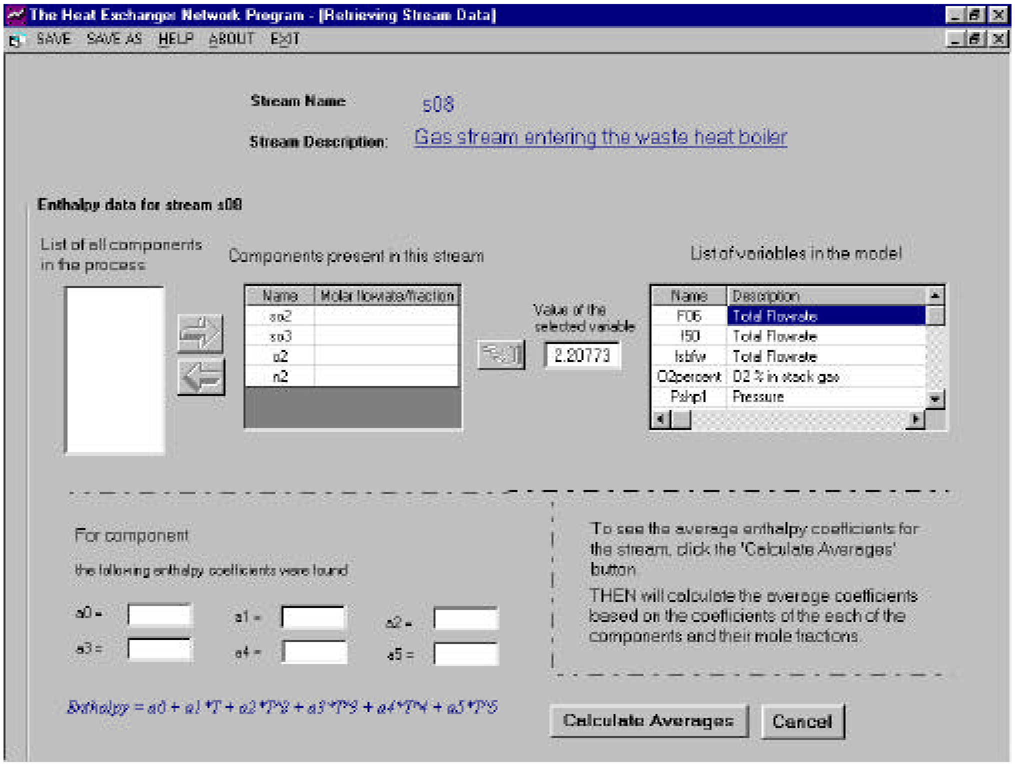
a0 =
a1 =
a2 =
a3 =
a4 =
a5 =

To see the average enthalpy coefficients for the stream, click the 'Calculate Averages' button.

THEN will calculate the average coefficients based on the coefficients of the each of the components and their mole fractions.

$Enthalpy = a0 + a1*T + a2*T^2 + a3*T^3 + a4*T^4 + a5*T^5$

Figure 67 The Enthalpy Data Window



Stream Name s08

Stream Description: Gas stream entering the waste heat boiler

Enthalpy data for stream s08

List of all components in the process

Components present in this stream

Name	Molar flowrate/fraction
so2	
so3	
o2	
n2	

Value of the selected variable 2.20773

List of variables in the model

Name	Description
F06	Total Flowrate
I50	Total Flowrate
lsbfw	Total Flowrate
O2percent	O2 % in stack gas
Pshp1	Pressure

For component

the following enthalpy coefficients were found

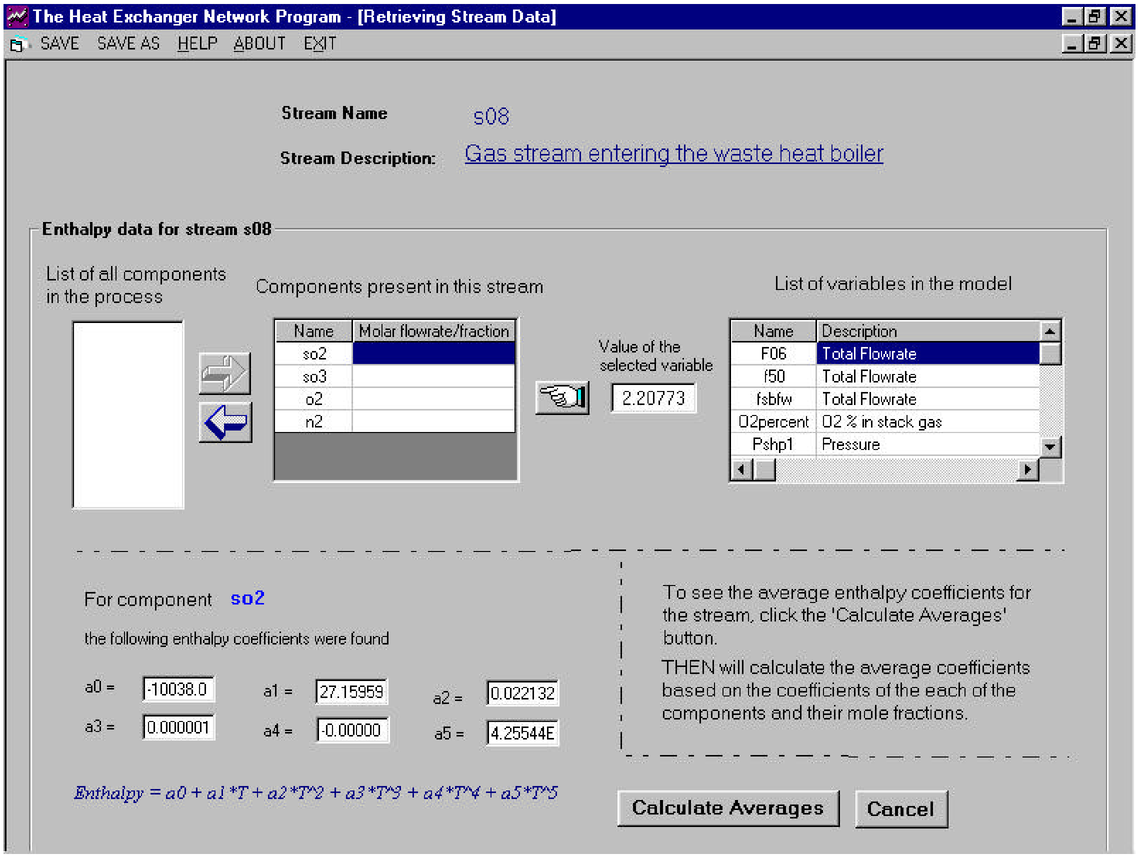
a0 =
a1 =
a2 =
a3 =
a4 =
a5 =

To see the average enthalpy coefficients for the stream, click the 'Calculate Averages' button.

THEN will calculate the average coefficients based on the coefficients of the each of the components and their mole fractions.

$Enthalpy = a0 + a1*T + a2*T^2 + a3*T^3 + a4*T^4 + a5*T^5$

Figure 68 The Enthalpy Window-2



Stream Name s08

Stream Description: Gas stream entering the waste heat boiler

Enthalpy data for stream s08

List of all components in the process

Components present in this stream

Name	Molar flowrate/fraction
so2	
so3	
o2	
n2	

Value of the selected variable 2.20773

List of variables in the model

Name	Description
F06	Total Flowrate
f50	Total Flowrate
fsbfw	Total Flowrate
O2percent	O2 % in stack gas
Pshp1	Pressure

For component **so2**

the following enthalpy coefficients were found

a0 = -10038.0 a1 = 27.15959 a2 = 0.022132

a3 = 0.000001 a4 = -0.00000 a5 = 4.25544E

To see the average enthalpy coefficients for the stream, click the 'Calculate Averages' button.

THEN will calculate the average coefficients based on the coefficients of the each of the components and their mole fractions.

Enthalpy = a0 + a1*T + a2*T^2 + a3*T^3 + a4*T^4 + a5*T^5

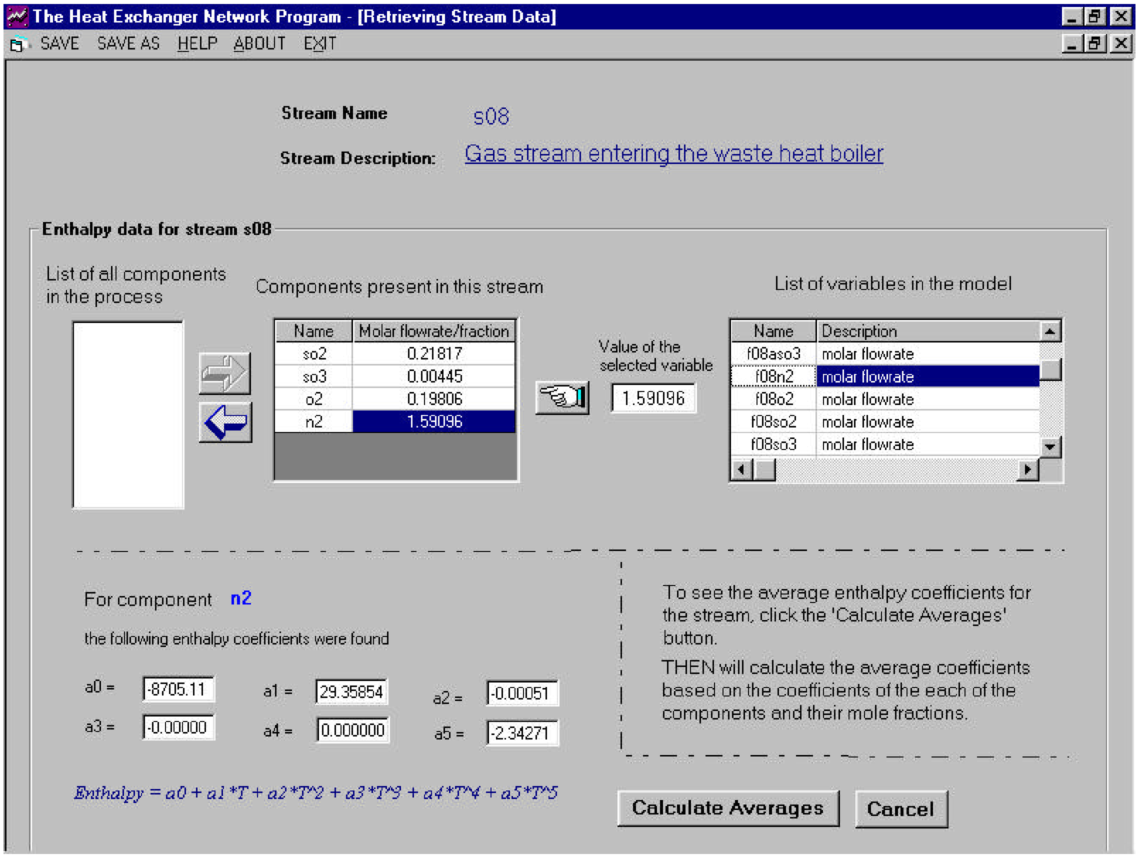
Figure 69 The Enthalpy Coefficients for SO_2

To calculate the average enthalpy coefficients of the stream, the stream composition and the enthalpy coefficients of the individual chemical components are needed. The enthalpy coefficients of the chemical components were entered in the Flowsim program. These can be viewed in the enthalpy window of C.VII.8 by simply clicking on the component name in the table ‘Components present in this stream’. For example, click on the first component SO_2. The bottom part of the window now shows the enthalpy coefficients for SO_2. This view is shown in Figure 69. Similarly, the enthalpy coefficients for all the other components can be viewed.

The second column of the table ‘Components present in this stream’ displays the molar flowrate or molar fraction of the component in the stream. As explained before, the average coefficients depend on the composition of the stream. The composition can be specified either in terms of molar flowrates of all the components or their molar fractions. These values have to be retrieved manually by the user. Let us retrieve the molar flowrates of the chemical components in stream s08.

The values we want to use for molar flowrates are from the results of on-line optimization. These values can be conveniently retrieved using the table ‘List of variables in the model’ on the right hand side of the widow. This window shows a list of all the variables (measured and unmeasured) with their descriptions. When a variable in this table is clicked, the value for that variable obtained as a result of economic optimization appears in the box titled ‘value of the selected variable’. The variable corresponding to molar flowrate of SO_2 in stream s08 is f08so2. Search for this variable in the table. The measured variables in the model are listed first followed by the unmeasured variables, both in alphabetical order. When the variable f08so2 is clicked in the table, its value appears in the adjacent box. Now, click on the ‘hand’ button to take this value as the molar flowrate of SO_2 in stream s08. The value is now copied into the table ‘Components present in this stream’ in the second column of the first row. Repeat this procedure for all the four components in the stream s08. The screen now looks like as shown in Figure 70.

Now that we have the composition of the stream s08 in terms of molar flowrates and the enthalpy coefficients of the individual components, the average enthalpy coefficients for the stream can be calculated. Click the ‘Calculate Averages’ button at the bottom of the window. The program now calculates the average enthalpy coefficients for stream s08 and displays them in the bottom left part of the screen. Also, the OK button at the bottom of the window now becomes visible. This view is shown in Figure 71.



Stream Name s08

Stream Description: Gas stream entering the waste heat boiler

Name	Molar flowrate/fraction
so2	0.21817
so3	0.00445
o2	0.19806
n2	1.59096

Value of the selected variable: 1.59096

Name	Description
f08aso3	molar flowrate
f08n2	molar flowrate
f08o2	molar flowrate
f08so2	molar flowrate
f08so3	molar flowrate

For component **n2**

the following enthalpy coefficients were found

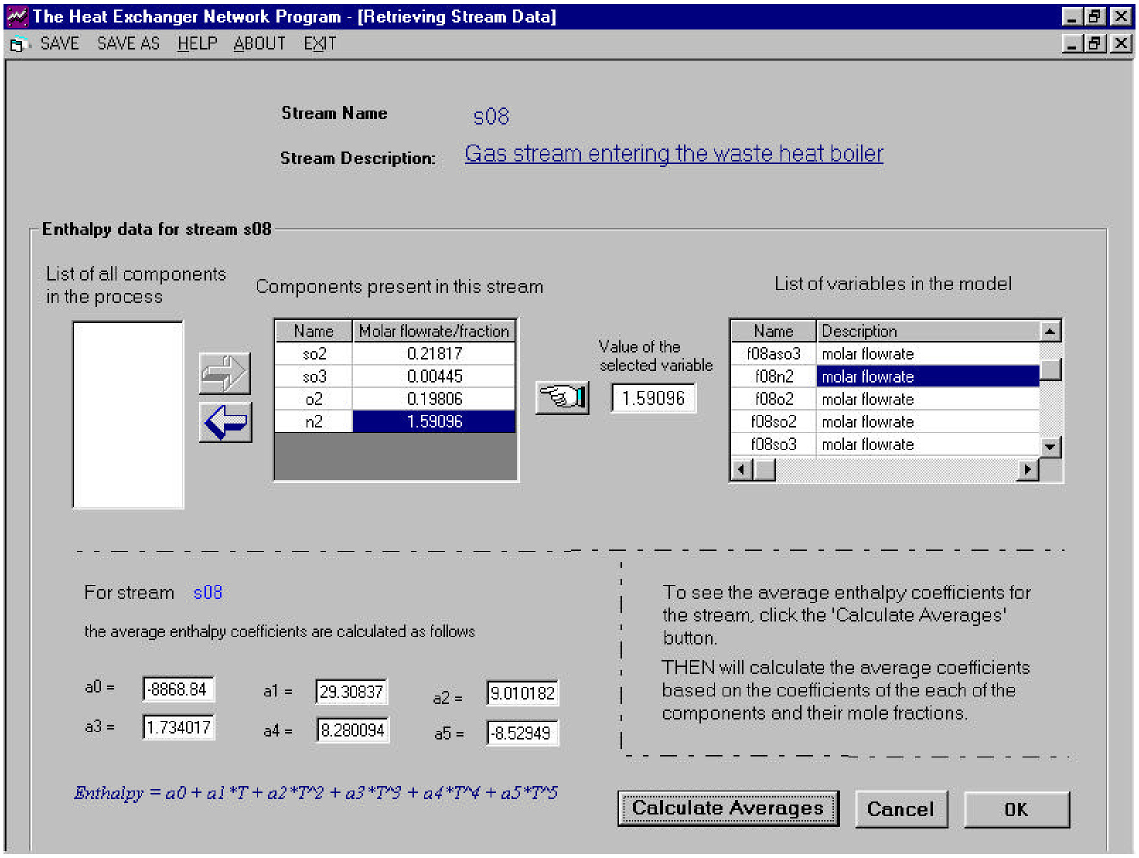
a0 = -8705.11
a1 = 29.35854
a2 = -0.00051
a3 = -0.00000
a4 = 0.000000
a5 = -2.34271

*Enthalpy = a0 + a1*T + a2*T^2 + a3*T^3 + a4*T^4 + a5*T^5*

To see the average enthalpy coefficients for the stream, click the 'Calculate Averages' button.

THEN will calculate the average coefficients based on the coefficients of the each of the components and their mole fractions.

Figure 70 The Molar Flowrates in Stream s08.



Stream Name s08

Stream Description: Gas stream entering the waste heat boiler

Enthalpy data for stream s08

List of all components in the process

Components present in this stream

Name	Molar flowrate/fraction
so2	0.21817
so3	0.00445
o2	0.19806
n2	1.59096

Value of the selected variable 1.59096

List of variables in the model

Name	Description
f08aso3	molar flowrate
f08n2	molar flowrate
f08o2	molar flowrate
f08so2	molar flowrate
f08so3	molar flowrate

For stream s08

the average enthalpy coefficients are calculated as follows

a0 = -8868.84
a1 = 29.30837
a2 = 9.010182
a3 = 1.734017
a4 = 8.280094
a5 = -8.52949

To see the average enthalpy coefficients for the stream, click the 'Calculate Averages' button.

THEN will calculate the average coefficients based on the coefficients of the each of the components and their mole fractions.

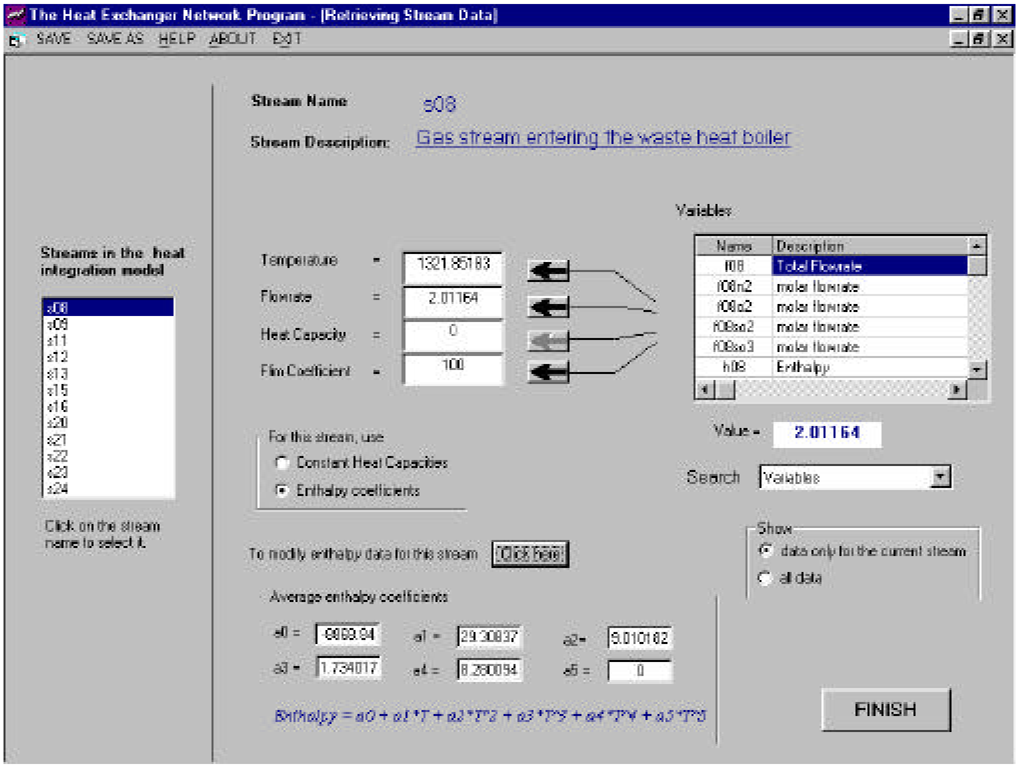
*Enthalpy = a0 + a1*T + a2*T^2 + a3*T^3 + a4*T^4 + a5*T^5*

Figure 71 The Average Enthalpy Coefficients of Stream s08.

If you want to accept the average coefficient values calculated by the program, click 'OK'. If the values do not appear to be in the expected range and are not acceptable, click the 'Cancel' button. For the stream s08, we will accept the calculated values and click the 'OK' button. The screen view now goes back to the 'Retrieving stream data' window shown in Figure 66. The fields for the average coefficients at the bottom of this window are now filled with the values calculated by the program. This view is shown in Figure 72.

Now, the temperature, flowrate and enthalpy coefficients data for stream s08 have been entered and can be seen in the Figure 72. The final piece of information is the film heat transfer coefficient value. For the Contact model, an average film coefficient value of 0.05675 KJ/sqft-K.sec is estimated for all the process streams. Change the default value of 100 to 0.05675 as the film coefficient for stream s08. This completes the data retrieval for stream s08.

This procedure should be repeated for all the streams listed on left side of the screen. For each of the streams, the temperature and flowrate will be automatically retrieved. The enthalpy coefficients should be calculated as done for stream s08. The film heat transfer coefficient values for all the streams should be 0.05675. The data retrieval part for Contact model is now complete and the 'Finish' button at the bottom of the screen should now be clicked.



Streams in the heat integration model

s08
s09
s11
s12
s13
s15
s16
s20
s21
s22
s23
s24

Click on the stream name to select it.

Stream Name: s08

Stream Description: Gas stream entering the waste heat boiler

Temperature = 1321.85183

Flowrate = 2.01164

Heat Capacity = 0

Film Coefficient = 100

Variables

Name	Description
f08	Total Flowrate
f08n2	molar flowrate
f08o2	molar flowrate
f08so2	molar flowrate
f08so3	molar flowrate
h08	Enthalpy

Value = 2.01164

Search: Variables

For this stream, use
○ Constant Heat Capacities
● Enthalpy coefficients

Show
● data only for the current stream
○ all data

To modify enthalpy data for this stream

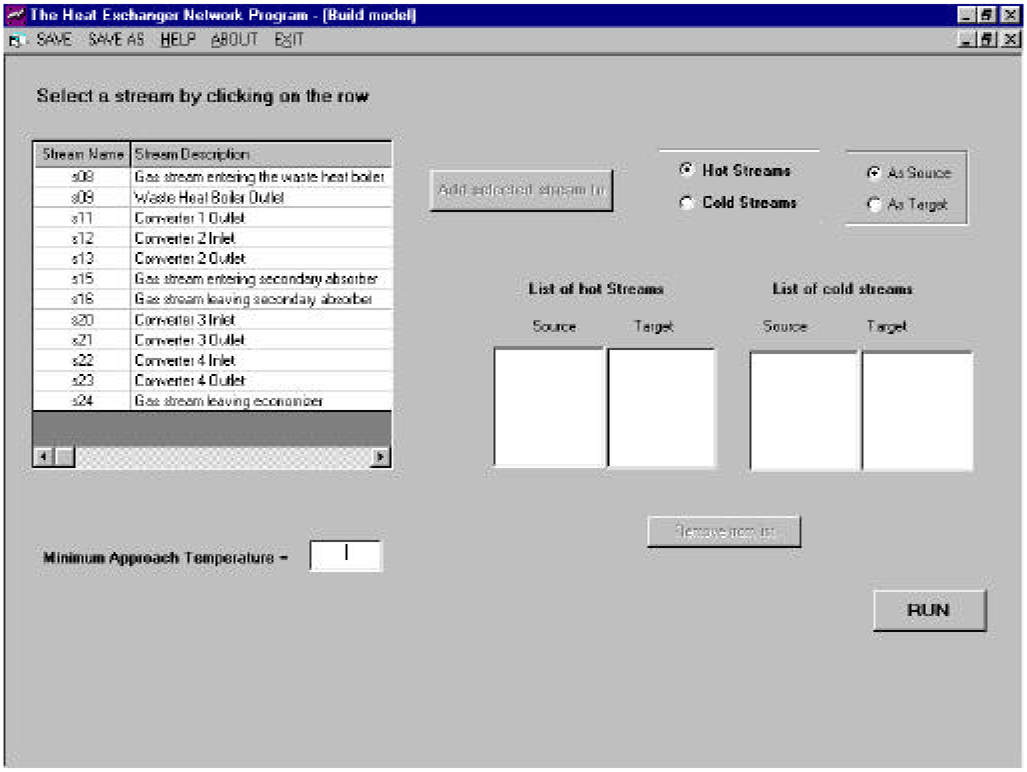
Average enthalpy coefficients

a0 = -9869.94 a1 = 29.30837 a2 = 5.010182

a3 = 1.734017 a4 = 8.280094 a5 = 0

Enthalpy = a0 + a1*T + a2*T^2 + a3*T^3 + a4*T^4 + a5*T^5

Figure 72 The Retrieving Stream Data Window-2.



Select a stream by clicking on the row

Stream Name	Stream Description
s08	Gas stream entering the waste heat boiler
s09	Waste Heat Boiler Outlet
s11	Converter 1 Outlet
s12	Converter 2 Inlet
s13	Converter 2 Outlet
s15	Gas stream entering secondary absorber
s16	Gas stream leaving secondary absorber
s20	Converter 3 Inlet
s21	Converter 3 Outlet
s22	Converter 4 Inlet
s23	Converter 4 Outlet
s24	Gas stream leaving economizer

● Hot Streams
○ Cold Streams

● As Source
○ As Target

List of hot Streams: Source, Target

List of cold streams: Source, Target

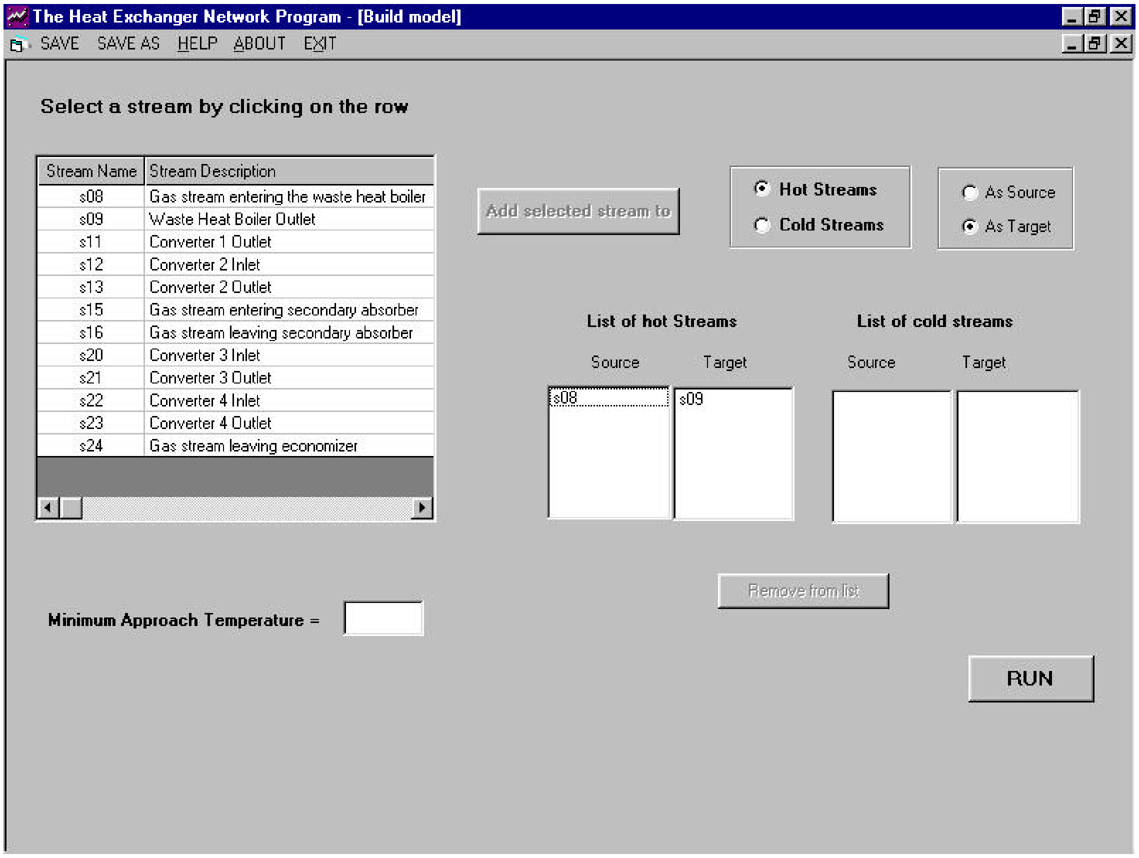
Minimum Approach Temperature = 1

Figure 73 The Build Model Window

When the ‘Finish’ button is clicked, the ‘Build Model’ window appears on the screen. This is shown in Figure 73. In this ‘Build Model’ window, the final step of dividing process streams into pairs of hot and cold streams is performed. This classification of streams constitutes the THEN model. In a THEN model, a hot stream is a stream that needs to be cooled and a cold stream is a stream that needs to be heated.

The table on the left side of the screen shows the list of process streams selected earlier in the program for heat integration. It shows the stream names as well as the descriptions. The two pairs of lists on the right side of the screen display the hot and cold streams in the stream model. Let us build the stream model for the Contact process.

From our knowledge of the D-train sulfuric acid process, we know that stream s08 enters the waste heat boiler and the stream s09 is the outlet stream from the boiler. Therefre, streams s08 and s09 are the source and targets respectively of a hot stream. To enter this hot stream, first select the stream s08 in the table. The button ‘Add selected stream to’ now becomes enabled. Select the ‘Hot Streams’ option and the ‘As source’ option. Now click the ‘Add selected stream to’ button. The stream s08 gets added to the list of hot streams as the source. Now click on the stream s09 in the table. Keep the ‘Hot Streams’ option and select ‘As target’ option this time. Now, s08 and s09 are both added to the hot streams list as source and target respectivey. These two constitute one hot stream. The screen view now is shown in Figure 74.



Select a stream by clicking on the row

Stream Name	Stream Description
s08	Gas stream entering the waste heat boiler
s09	Waste Heat Boiler Outlet
s11	Converter 1 Outlet
s12	Converter 2 Inlet
s13	Converter 2 Outlet
s15	Gas stream entering secondary absorber
s16	Gas stream leaving secondary absorber
s20	Converter 3 Inlet
s21	Converter 3 Outlet
s22	Converter 4 Inlet
s23	Converter 4 Outlet
s24	Gas stream leaving economizer

● Hot Streams
○ Cold Streams

○ As Source
● As Target

List of hot Streams

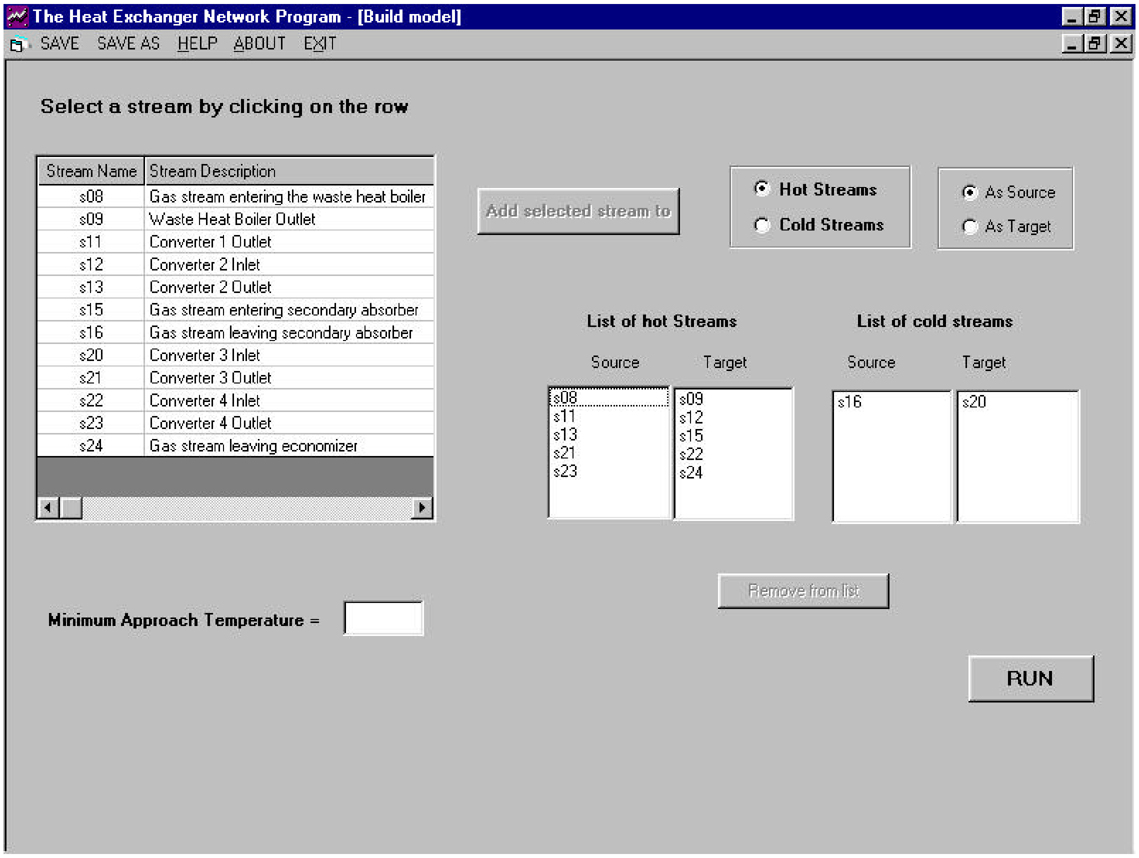
Source	Target
s08	s09

List of cold streams

Source	Target

Minimum Approach Temperature =

Figure 74 The Build Model Window with one Hot Stream



Select a stream by clicking on the row

Stream Name	Stream Description
s08	Gas stream entering the waste heat boiler
s09	Waste Heat Boiler Outlet
s11	Converter 1 Outlet
s12	Converter 2 Inlet
s13	Converter 2 Outlet
s15	Gas stream entering secondary absorber
s16	Gas stream leaving secondary absorber
s20	Converter 3 Inlet
s21	Converter 3 Outlet
s22	Converter 4 Inlet
s23	Converter 4 Outlet
s24	Gas stream leaving economizer

● Hot Streams
○ Cold Streams

● As Source
○ As Target

List of hot Streams

Source	Target
s08 s11 s13 s21 s23	s09 s12 s15 s22 s24

List of cold streams

Source	Target
s16	s20

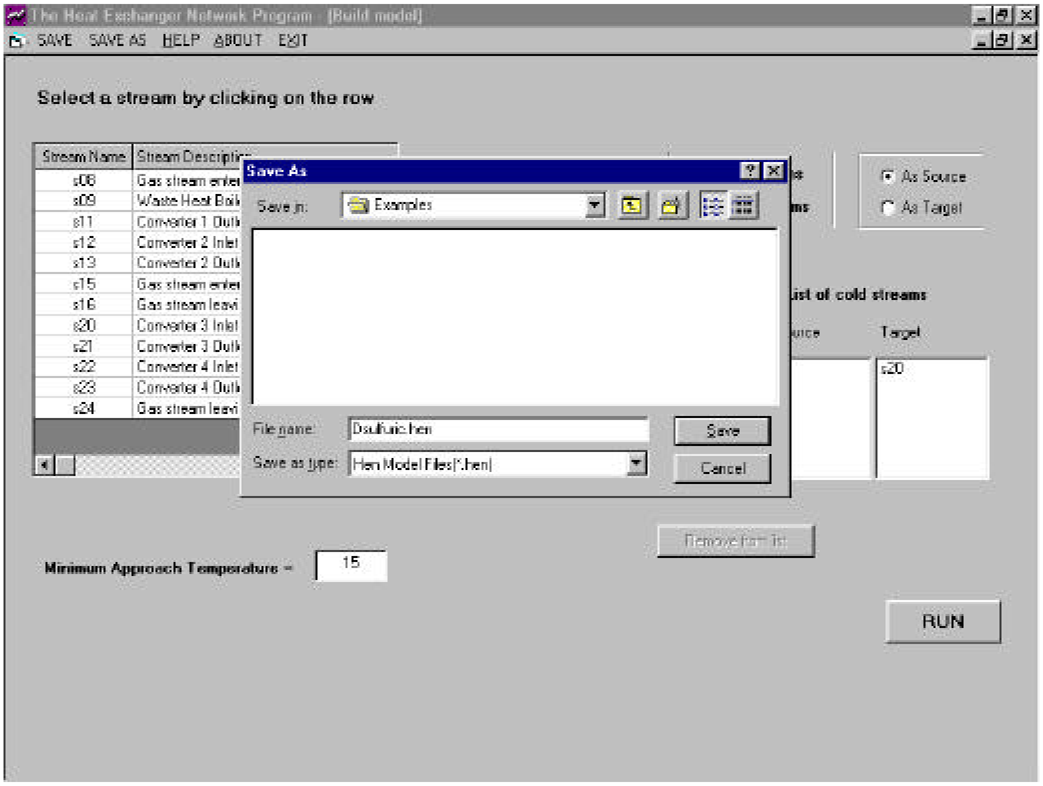
Minimum Approach Temperature =

Figure 75 The Build Model Window with all the Hot and Cold Streams

Repeat this procedure for all the other streams. The hot stream pairs for the Contact process are s08-s09, s11-s12, s13-s15, s21-s22 and s23-s24. There is only one cold stream pair, s16-s20. In all of these pairs, the first stream is the source and the second stream is the target. Once, we have entered all of these streams, the THEN model for the Contact process is complete. The 'Build Model' window with all the hot and cold streams is shown in Figure 75. The last piece of information needed is the minimum approach temperature between the streams. There is no fixed recommended value for this. We will enter an approach tempearture of 15 °C to ensure that there is sufficient driving force for heat exchange between the streams.

The input part of the program is now over. Let us save the information entered so far by clicking the 'Save' button. The program displays the 'Save As' window shown in Figure 76. Save the model as 'Dulfuric.hen' in the 'Examples' subdirectory of the program folder.

Now, click the 'Run' button on the 'Build Model' window. The program uses all of the information entered above and appiles concepts of pinch analysis to the Contact process. The next window that appears on the screen is the 'Output Window' shown in Figure 77.



Select a stream by clicking on the row

Stream Name	Stream Descriptio
s08	Gas stream enter
s09	Waste Heat Boil
s11	Converter 1 Outl
s12	Converter 2 Inlet
s13	Converter 2 Outl
s15	Gas stream enter
s16	Gas stream leavi
s20	Converter 3 Inlet
s21	Converter 3 Outl
s22	Converter 4 Inlet
s23	Converter 4 Outl
s24	Gas stream leavi

Save in: Examples

File name: Dsulfuric.hen

Save as type: Hen Model Files(*.hen)

● As Source

○ As Target

Target: s20

Minimum Approach Temperature = 15

Figure 76 The Save As Window

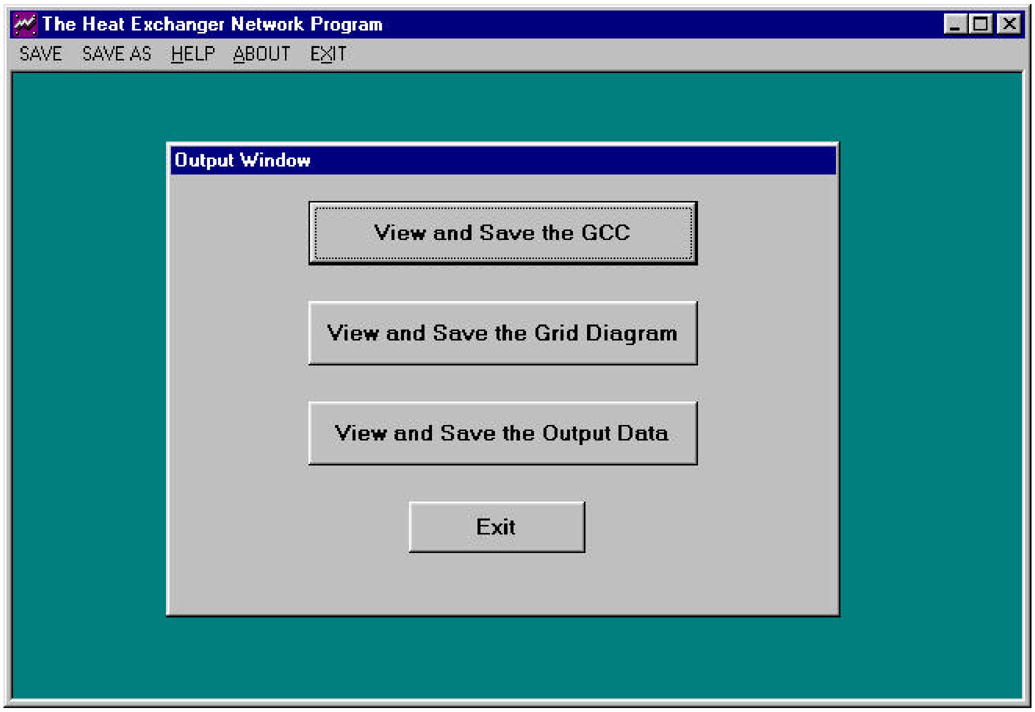


Figure 77 The Output Window

Clicking the first button ‘View and save the GCC’ on the 'Output Window' displays the 'Grand Composite Curve' on the screen. This is shown in Figure 78. It is a plot of enthalpy flows in the system versus temperature. The units for temperature and enthalpy are the same as for the input data entered. The temperatures are in Kelvin and enthalpies are in KJ/s. As seen in Figure 78, the curve touches the temperature-axis at its highest point. This is a ‘below the pinch’ problem. The process needs only cold external utility. The amount of cold utility is the enthalpy coordinate of the lowest point of the curve. This is about 85000 KJ/s as seen in the diagram. The exact amount of the cold utility can be seen in the output file, which is explained later.

The menu bar at the top of the diagram provides options for viewing and printing the diagram. Clicking the 'View' button displays the commands to turn off the grid and show the data points. The 'Print Options' button can be used to set the number of copies and change the printer orientation. Clicking the 'Print' button will print the diagram to the default system printer. Click the 'Save' button to save the diagram in 'Windows Metafile’ format. The 'Help' button will display a brief description about the Grand Composite Curve. Closing the window brings the user back to the 'Output Window'.

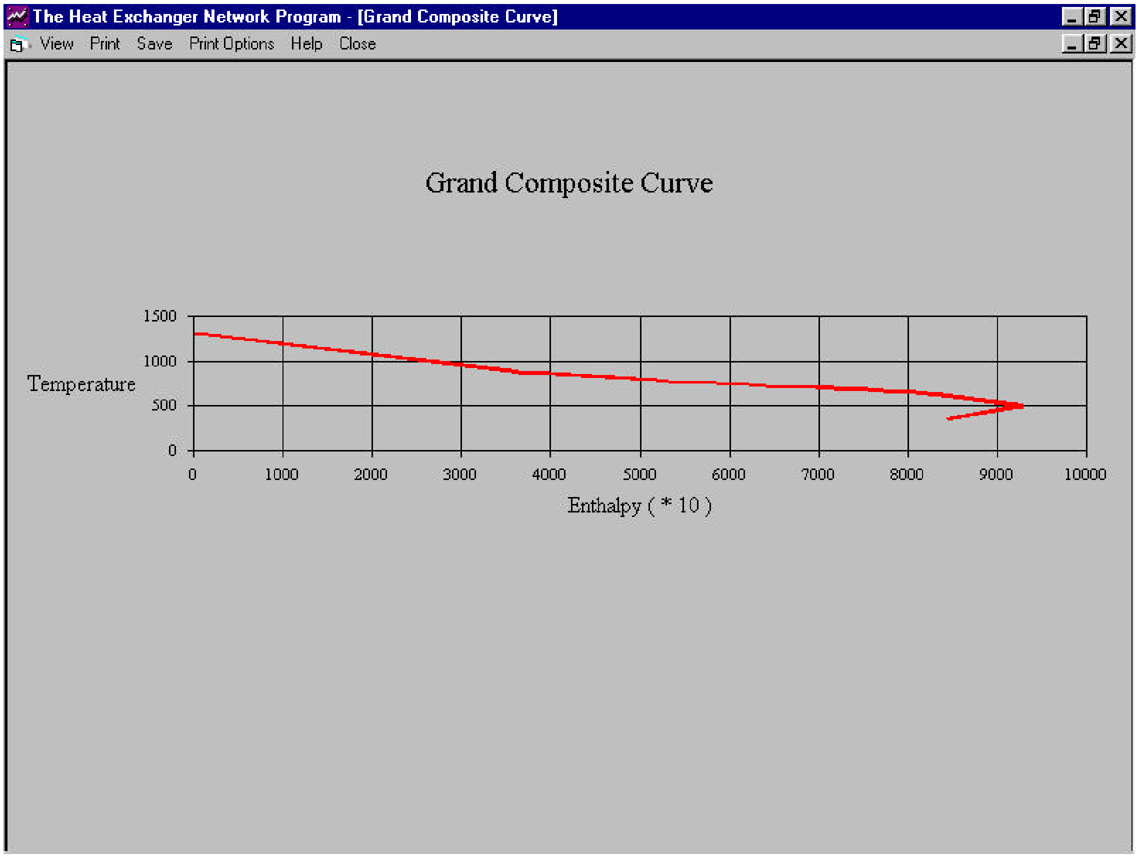
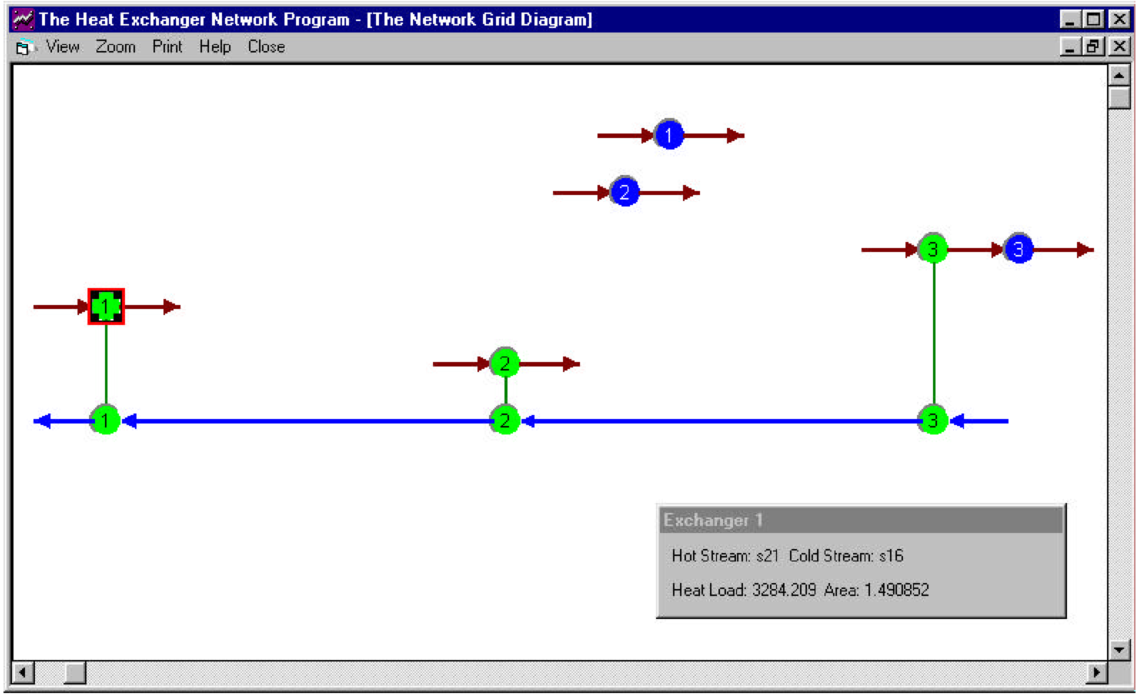


Figure 78 The Grand Composite Curve



Exchanger 1

Hot Stream: s21 Cold Stream: s16

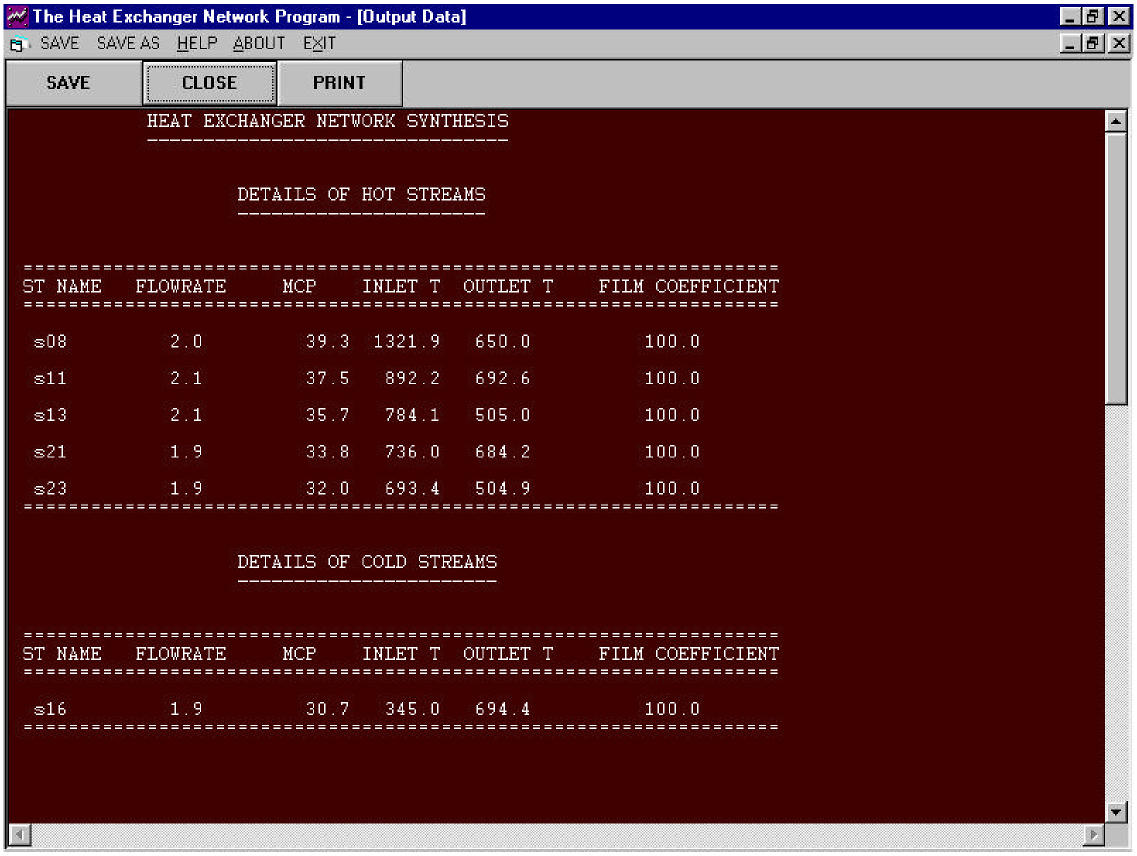
Heat Load: 3284.209 Area: 1.490852

Figure 79 The Network Grid Diagram

The second button ‘View and save the Grid Diagram’ on the 'Output Window' displays the 'Network Grid Diagram'. This is shown in Figure 79. It is a graphical representation of the network solution designed by the program. It shows the arrangement of heat exchangers, heaters and coolers in the system. Red lines going from left to right represent hot streams and blue lines going from right to left represent cold streams. A red circle on a blue line means a heater and a blue circle on a red line is a cooler. Green circles joined by a vertical green line represent a heat exchanger between the streams on which the two circles lie

The network grid diagram offers a very convenient way of understanding the solution network. Clicking on a unit in the diagram displays a small box, which shows all the necessary information for that unit. For example, clicking on a green circle will display the relevant information for the heat exchanger that it represents. This information includes the names of the hot and cold streams flowing through it, the heat exchange load of the exchanger and its area. Clicking on a heater or a cooler will show the name of the stream flowing through it and its heat load. Similarly, clicking on a horizontal line will display the temperature, mass flowrate and average heat capacity of that stream. In Figure 79, the heat exchanger with index 1 has been selected by clicking, and the box at the bottom right side is showing the information for that heat exchanger.

Information about the grid diagram can be obtained as online help by clicking the 'Help' button in the menu bar at the top of the diagram. Other buttons in the menu bar are to set the view and print options. The 'Zoom' button allows the user to change the zoom of the diagram. The 'View' button can be used to display the printer lines. The 'Print' button will open the printer dialog box and print the diagram to the selected printer. Closing the window will take the user back to the 'Output Window'.



```
             HEAT EXCHANGER NETWORK SYNTHESIS
             --------------------------------


                     DETAILS OF HOT STREAMS
                     ----------------------


===================================================================
ST NAME   FLOWRATE     MCP    INLET T  OUTLET T    FILM COEFFICIENT
===================================================================

 s08         2.0         39.3  1321.9   650.0          100.0

 s11         2.1         37.5   892.2   692.6          100.0

 s13         2.1         35.7   784.1   505.0          100.0

 s21         1.9         33.8   736.0   684.2          100.0

 s23         1.9         32.0   693.4   504.9          100.0
===================================================================

                     DETAILS OF COLD STREAMS
                     -----------------------


===================================================================
ST NAME   FLOWRATE     MCP    INLET T  OUTLET T    FILM COEFFICIENT
===================================================================

 s16         1.9         30.7   345.0   694.4          100.0
===================================================================
```

Figure 80 The Ouput Data Window

The third button in the output window, the ‘View and save the Output Data’ button shows the output text file in a window as shown in Figure 80. Using horizontal and vertical scroll bars, the user can see the entire output text. The 'Print' button at the top of the window prints output file to the default printer. On clicking the ‘Save’ button, the program opens the 'Save as' window and requests the user to specify the filename. Let us save the output as file 'out.dat' in the Examples subdirectory of the program folder. Click the 'Close' button to go back to the Output Menu window.

The execution of the THEN program is complete. The results have been displayed in the form grand composite curve, network grid diagram and the output data file. Let us look at the results more closely and interpret the solution generated by THEN.

Using the Results from THEN

<u>The Grand Composite Curve (GCC)</u>: The GCC for the Contact process is shown in Figure 78. It is a plot of temperature on Y-axis versus the enthalpy flow on X-axis. If the curve touches the temperature-axis except at its endpoints, it is a pinched process, and the temperature corresponding to that point is the pinch temperature. If the curve touches the X-axis at its uppermost point, the process is ‘below the pinch’. If it touches at the lowermost point, it is an

‘above the pinch’ process. In Figure 78, the GCC meets the temperature axis at its uppermost point. Hence, it is a ‘below the pinch’ process.

Also, the GCC can be used to determine the minimum amount of hot and cold utilities needed by the process. To find the amount of hot utility required, locate the topmost point of the curve and read its X coordinate which is equal to the amount of hot utility. Similarly, to get the amount of cold utility required, locate the bottommost point of the curve and read its X coordinate. For the Contact process, from Figure 78, it can be seen that the amount of hot utility is zero and the amount of cold utility is about 85000 KJ/s.

The Network Grid Diagram:

The network grid diagram for the Contact process is shown in Figure 78. Let us examine this diagram to understand the new heat exchanger network structure for this process. The five horizontal red lines at the top running from left to right represent the hot streams s08, s11, s13, s21 and s23. The horizontal blue line at the bottom running from right to left represents the cold stream s16. The blue circles (numbered 1, 2, 3) on streams H1 and H2 indicate that these three streams require coolers. There are no red circles in the diagram indicating the absence of any heater. There are three pairs of green circles (numbered 1, 2, 3) joined by vertical green lines. These represent the three heat exchangers in the process. Each exchanger exchanges heat between the two streams on which the two circles lie. For example, heat exchanger 1 (the pair of green circles with number 1) is exchanging heat between hot stream s21 and cold stream s16. Thus, it can been seen from the grid diagram that the Contact process needs three heat exchangers, no heaters and three coolers in the new network solution.

The Output Data File:

Now, let us examine the output data generated by THEN. The complete output file for the above problem is given in Table 7. In Table 7, the first two sections ‘Details of hot stream’ and ‘Details of cold stream’ list a summary of the input information entered by the user. This consists of the data for hot and cold streams followed by the specified minimum approach temperature for the matches.

The input summary is followed by the results for the simple process. The first two lines of output mean that the given problem was a ‘below the pinch’ problem.

This is followed by a matrix of values which is the solution array generated by THEN for the problem above the pinch. These values can help in understanding the matches made by the program to arrive at the solution. However, the most important part of the output is the Heat Exchangers, Heaters and Coolers summary tables, which follow.

The heat exchanger summary above the pinch shows that there should be three heat exchangers, each between streams s16-s21, s16-s23 and s16-s13, For exchanger 1 between s16 and s13, the heat transfer rate will be 3280 KJ/s. Also, it gives the inlet and outlet temperatures for both the streams. Note that the area of the heat exchanger (2627 ft^2) has been calculated using the film heat transfer coefficient supplied in the data.

Table 7 THEN Solution for the Contact Process - Output Data File

```
                    DETAILS OF HOT STREAMS

ST NAME   FLOWRATE     MCP    INLET T  OUTLET T    FILM COEFFICIENT

  s08         2.0       39.3   1321.9    650.0             .1
  s11         2.1       37.5   892.2     692.6             .1
  s13         2.1       35.7   784.1     505.0             .1
  s21         1.9       33.8   736.0     684.2             .1
  s23         1.9       32.0   693.4     504.9             .1

                   DETAILS OF COLD STREAMS

ST NAME   FLOWRATE     MCP    INLET T  OUTLET T    FILM COEFFICIENT

  s16         1.9      30.7   345.0   694.4             .1

 MINIMUM DELTA T FOR THE MATCHES IS  15.00  DEG

 UNPINCHED PROBLEM

 PROB. BELOW PINCH

 ALL STRMS EXHAUSTED

        .0      .0      .0      .0     1.0
        .0      .0      .0      .0    57.9
        .0      .0      .0      .0   352.5
        .0      .0      .0      .0      .0
       1.0    79.0  1314.4 53101.1      .0
       2.0    80.0   884.7 15980.5      .0
       3.0    75.1   700.9 15268.5  5677.7
       4.0    63.4   676.7      .0  3284.2
       5.0    59.8   497.4      .0 11277.3

HEAT EXCHANGER SUMMARY BELOW PINCH

HEX  CS  HS   HEAT    THIN  THOUT   TCIN    TCOUT    CPH     CPC      AREA

1.  s16 s21 .328E+04 736.03 684.22  637.68 694.37  .63E+02  .58E+02 2627.052
2.  s16 s23 .113E+05 693.41 504.92  443.01 637.68  .60E+02  .58E+02 6763.037
3.  s16 s13 .568E+04 784.07 708.42  345.00 443.01  .75E+02  .58E+02  568.262

 COOLER SUMMARY BELOW THE PINCH

      COOLER      CNO     HEAT        THIN       THOUT       CPH

       1.0        1.0    53101.1     1321.9      650.0       79.0
       2.0        2.0    15980.5      892.2      692.6       80.0
       3.0        3.0    15268.5      708.4      505.0       75.1

 NO LOOPS PRESENT IN THIS NETWORK

 THE MINIMUM HOT UTILITY REQUIREMENT IS:   0.000000E+00

 THE MINIMUM COLD UTILITY REQUIREMENT IS:   85073.790000
```

Next comes the cooler summary above the pinch. It shows that we need three coolers in the system, one for each hot stream. The cooling load for the cooler on the stream s08 is 53.101 MJ/s. Stream s08 enters the cooler at 1321 K and leaves at 650 K. Similarly, the other coolers have cooling loads of 15.98 and 15.26 MJ/s respectively.

Next comes the information about the loops identified in the network. A loop is any path in the heat exchanger network that starts at some point and returns to the same point. For the Contact process, there are no loops in the network.

Finally, the last two lines of output give the minimum hot and cold utilities needed for this process. Thus, for the Contact process, 85073.79 KJ/s of heat needs to be removed by use of external cold utilities. No hot utility is needed.

Note that just above the printout of the solution array is a message which says if all the streams were exhausted or not. If the message is ‘all streams exhausted’, THEN has successfully generated the heat exchanger network. If the message is ‘Error- not all streams exhausted’, THEN has failed to solve the problem. In this case, the order of the streams in the input data should be changed. For example, the data for stream s11 should be entered before stream s08. The program uses a solution method that is sensitive to the order in which the stream data is entered.

To summarize, the Contact process is a ‘below the pinch’ process, and it needs 3 heat exchangers and 3 coolers for maximum energy utilization. The minimum amount of cold utility is 85073.79 KJ/s and the minimum amount of hot utility is zero.

This concludes the implementation of the Heat Exchanger Network program in the Advanced Process Analysis System. The next step of the Advanced Process Analysis System is calculation of pollution indices. Click on the ‘Pollution Index’ button in the Advanced Process Analysis Desk to call the pollution index program.

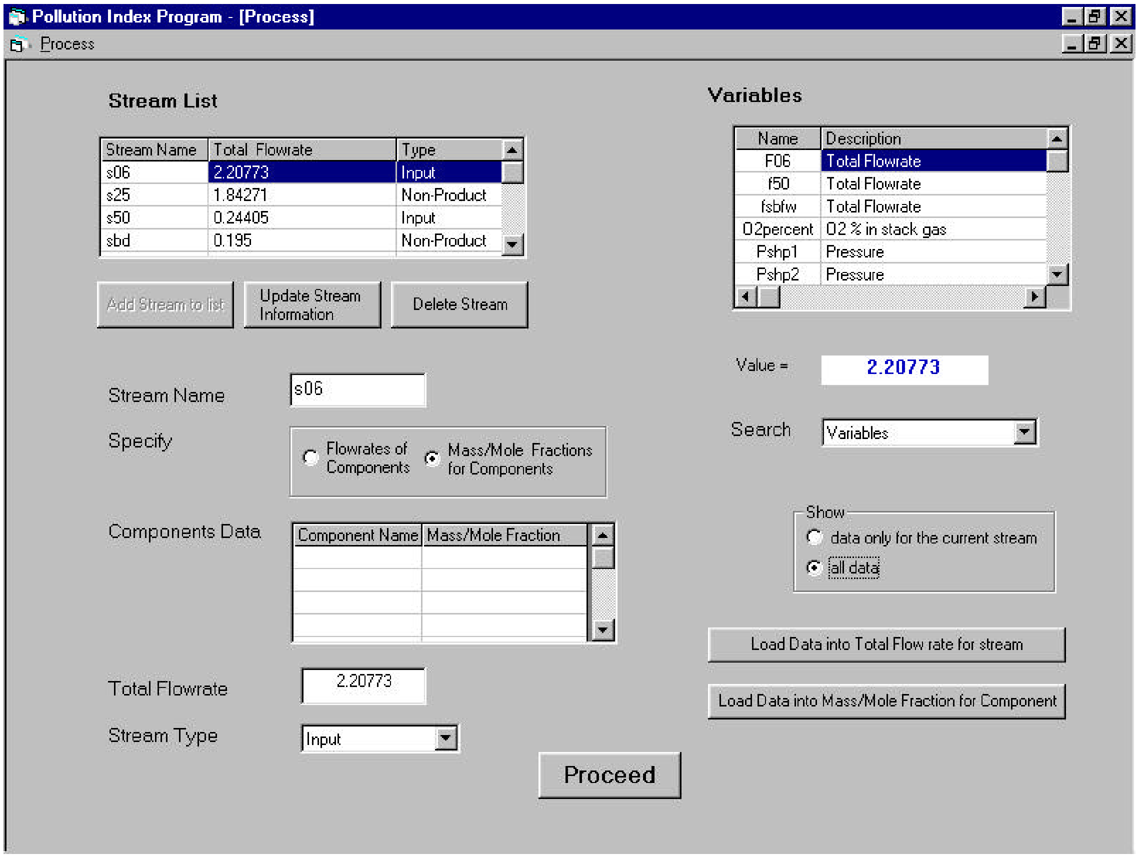
VIII. USING THE POLLUTION INDEX PROGRAM

Upon clicking the ‘Pollution Index’ button in the Advanced Process Analysis Desk, the first window presented to the user is the ‘Process’ window shown in Figure 81.

The table ‘Stream List’ shows the list of all input and output streams in the process. This list is automatically retrieved based on the flowsheet diagram drawn by the user. The total molar flowrates of the streams are also retrieved and are shown in the second column of the table. The third column gives the type of the stream. As discussed in Section I, the streams important for pollution index calculations are the input and output streams, and the output streams are further divided into product and non-product streams. In the table shown in Figure 81, the classification of streams into input and output is automatically done. The further classification of output streams into product and non-product needs to be done by the user. By default, all output streams are assumed to be products.

Calculation of pollution indices requires the composition of the process streams. The composition can be specified either in terms of molar flowrates or mole fractions. These values can be conveniently retrieved from the results of on-line optimization. Let us retrieve the values for the first stream in the list, s06. Click on the stream, s06 in the table 'Stream List' in Figure 81. Choose the radio button with the option 'Flowrates of components' to specify the composition. Now, let us retrieve the flowrates of the individual components in stream s06 as described below.

In Figure 81 the table 'Variables' on the right-hand side at the top shows the names and descriptions of all the measured and unmeasured variables in the contact process model. Select the radio button for the option 'data only for the current stream'. When this option is selected, the table 'Variables' only shows the variables that are associated with that stream. The screen view now is shown in Figure 82 The variables associated with stream s06 can be seen in the table 'Variables' in Figure 82. Stream s06 is the inlet air stream, and it contains oxygen and nitrogen. In the 'Variables' table, f06n2 and f06o2 are the molar flowrates of nitrogen and oxygen respectively in stream s06. Let us enter these values in the 'Components Data' table as described below.



Stream List

Stream Name	Total Flowrate	Type
s06	2.20773	Input
s25	1.84271	Non-Product
s50	0.24405	Input
sbd	0.195	Non-Product

Stream Name: s06

Specify: ○ Flowrates of Components ● Mass/Mole Fractions for Components

Components Data

Component Name	Mass/Mole Fraction

Total Flowrate: 2.20773

Stream Type: Input

Variables

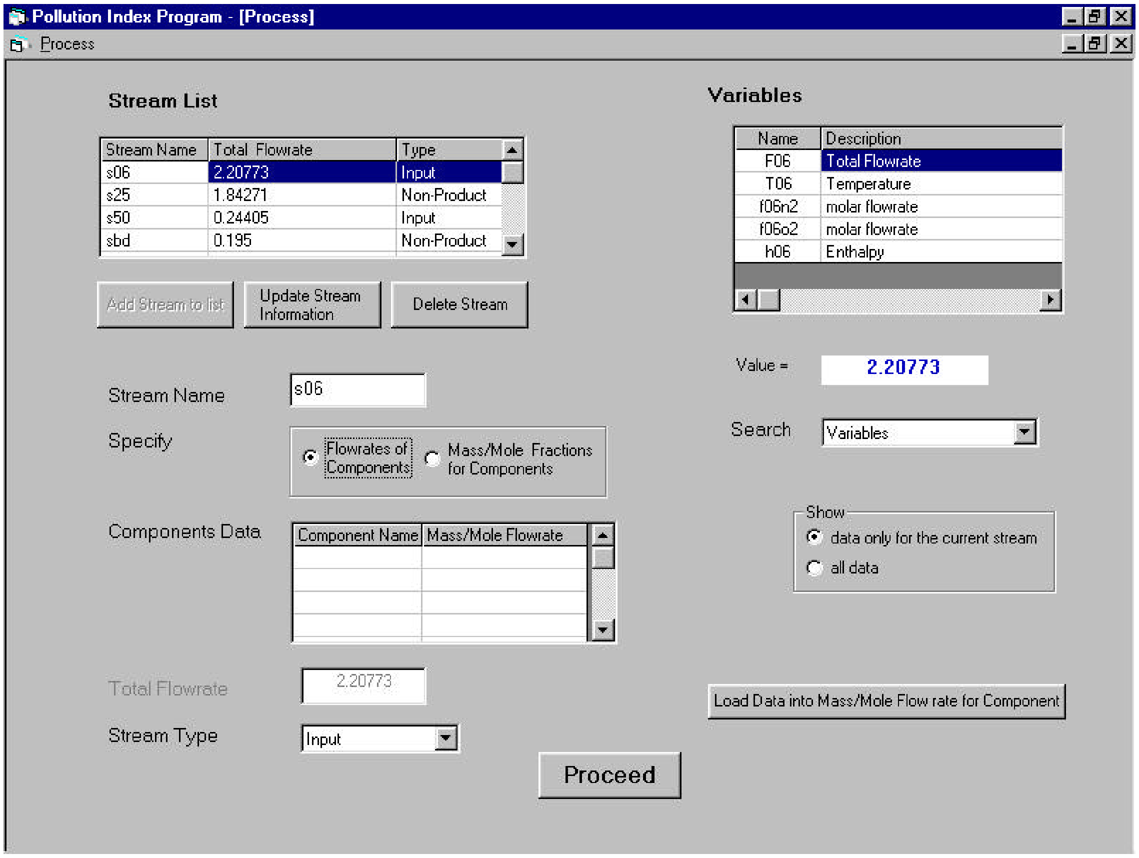
Name	Description
F06	Total Flowrate
f50	Total Flowrate
fsbfw	Total Flowrate
O2percent	O2 % in stack gas
Pshp1	Pressure
Pshp2	Pressure

Value = 2.20773

Search: Variables

Show
○ data only for the current stream
● all data

Figure 81 The Process Window of the Pollution Index Program



Stream List

Stream Name	Total Flowrate	Type
s06	2.20773	Input
s25	1.84271	Non-Product
s50	0.24405	Input
sbd	0.195	Non-Product

Variables

Name	Description
F06	Total Flowrate
T06	Temperature
f06n2	molar flowrate
f06o2	molar flowrate
h06	Enthalpy

Value = 2.20773

Search: Variables

Stream Name: s06

Specify: ● Flowrates of Components ○ Mass/Mole Fractions for Components

Components Data

Component Name	Mass/Mole Flowrate

Show: ● data only for the current stream ○ all data

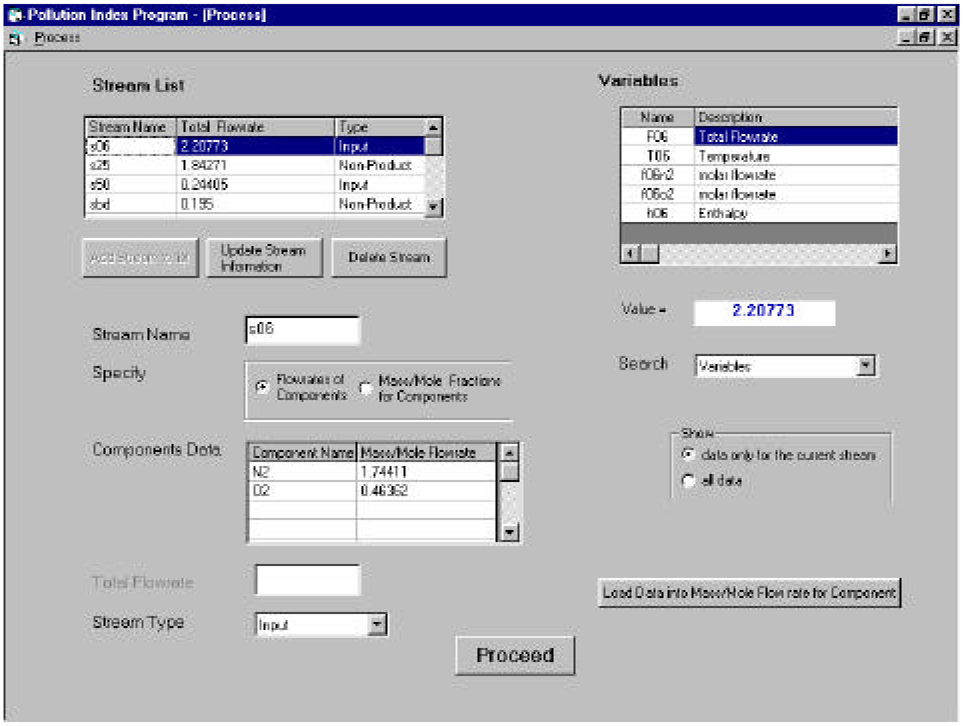
Total Flowrate: 2.20773

Stream Type: Input

Figure 82 The Process Screen with Stream s06

In the ‘Component Data’ table, enter N2 in the first row of the component name column. Now click on the variable f06n2 in the ‘Variables’ table. The value field below the ‘Variables’ table now shows the value of f06n2 obtained as a result of economic optimization. To take this value as the molar flowrate of N2, click the button ‘Load Data into Mass/Mole Flowrate for Component’. The next component in stream s06 is oxygen. Enter O2 in the second row of the ‘Components Data’ table. Click on the variable ‘f06O2’ in the ‘Variables’ table and then click the button ‘Load Data into Mass/Mole Flowrate for Component’. Both the components of the stream s06 have been entered and the composition of stream s06 is now completely specified. The stream type of stream s06 is ‘input’ as correctly determined by the program. The screen view now is shown in Figure 83 The above changes made to the composition data for stream s06 need to be updated. Click on the ‘Update Stream Information’ button to save the changes.

Repeat the same procedure for all the other streams in the table ‘Stream List’. Click on each stream in the table. Enter the component names and retrieve their flowrates from the ‘Variables’ table. If you do not see the required variable in the table, choose the ‘all data’ option. For the output streams, change the default type from ‘product’ to ‘non-product’ wherever necessary. In the contact process, the stream s25, the stack gas and the stream sbd, the boiler blowdown are the non-product streams. For each stream, after the changes are done, click the ‘Update Stream Information’ button.



Stream List

Stream Name	Total Flowrate	Type
s06	2.20773	Input
s25	1.84271	Non-Product
s50	0.24405	Input
sbd	0.195	Non-Product

Stream Name: s06

Specify: ● Flowrates of Components ○ Mass/Mole Fractions for Components

Components Data

Component Name	Mass/Mole Flowrate
N2	1.74411
O2	0.46362

Total Flowrate:

Stream Type: Input

Variables

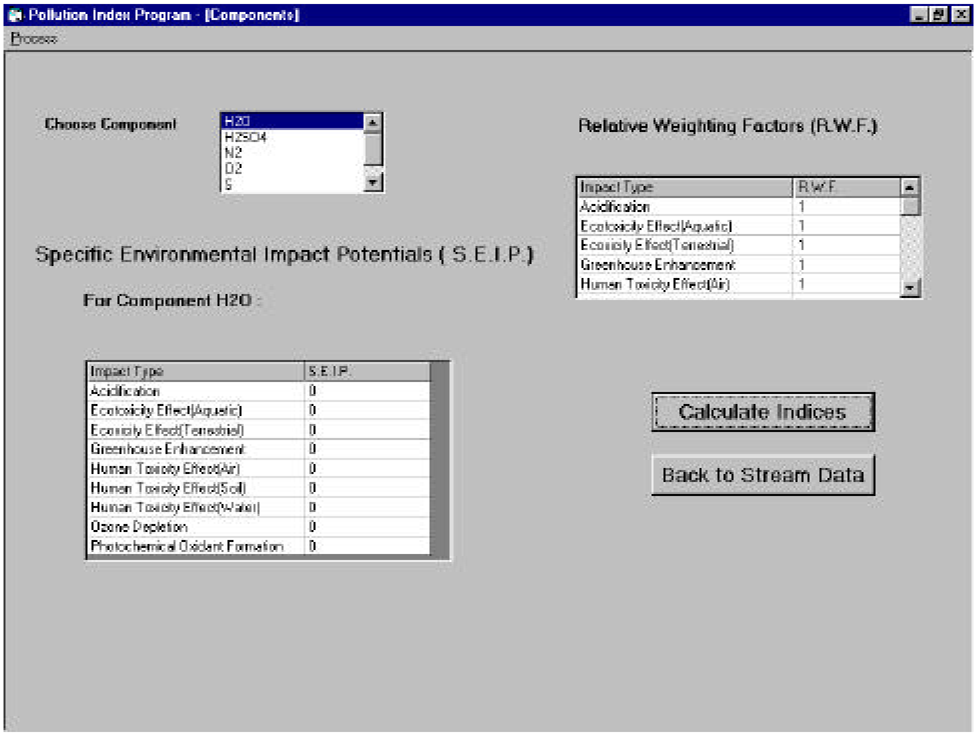
Name	Description
F06	Total Flowrate
T06	Temperature
f06n2	molar flowrate
f06o2	molar flowrate
h06	Enthalpy

Value = 2.20773

Search: Variables

Show
● data only for the current stream
○ all data

Figure 83The Composition Data for Stream s06.



Choose Component: H2O (selected), H2SO4, N2, O2, S

Relative Weighting Factors (R.W.F.)

Impact Type	R.W.F.
Acidification	1
Ecotoxicity Effect(Aquatic)	1
Ecoxicity Effect(Terrestrial)	1
Greenhouse Enhancement	1
Human Toxicity Effect(Air)	1

Specific Environmental Impact Potentials (S.E.I.P.)

For Component H2O :

Impact Type	S.E.I.P.
Acidification	0
Ecotoxicity Effect(Aquatic)	0
Ecoxicity Effect(Terrestrial)	0
Greenhouse Enhancement	0
Human Toxicity Effect(Air)	0
Human Toxicity Effect(Soil)	0
Human Toxicity Effect(Water)	0
Ozone Depletion	0
Photochemical Oxidant Formation	0

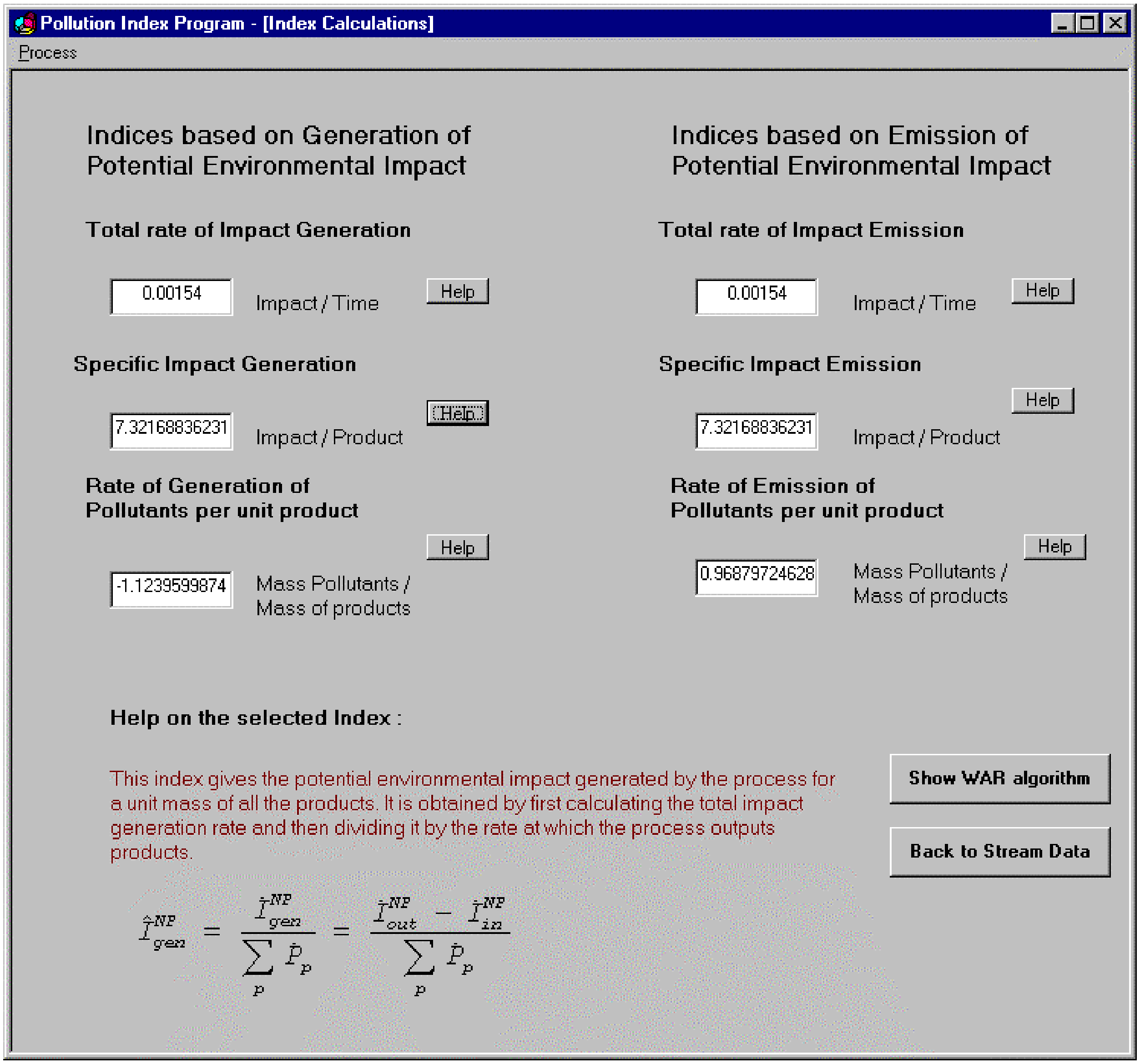
Figure 84The Components Window

When the composition information for all the streams in table ‘Stream List’ has been entered, click the ‘Proceed’ button. The ‘Components’ window is now displayed on the screen. This is shown in Figure 84 This window is used to enter the specific environmental impact potentials of the various components in the process. As discussed in Section I, there are nine categories of environmental impacts. The specific environmental impact potential values have to be entered for each component for each of the nine types of impact.

The ‘Choose Component’ table gives a list of all the components present in the input and output streams of the model. The impact potentials values for the components of the contact process were obtained from report on environmental life cycle assessment of products (Heijungs, 1992) published by EPA. The specific environmental impact potentials for O_2, N_2, S, H_2O and H_2SO_4 are zero for all nine categories of impact. The impact potentials of SO_2 are 1 for acidification and 1.2 for human toxicity effect on air. For the other seven categories, SO_2 impact potentials are zero.

Since the default values of all impact potentials in the program are zero, only the values for SO_2 need to be changed. Scroll down in the component list and select SO_2. Now click on the S.E.I.P. (specific environmental impact potentials) column in the first row. This row is for the impact type ‘acidification’. Enter the value 1. Click on the impact type ‘Human Toxicity Effect (Air)’ and enter 1.2. Leave the values for other types at zero. The final piece of information needed is the relative weighting factors. For the contact process, let us keep the default values of one for all the weighting factors. All of the information necessary for the calculation of pollution indices has been entered in the program. Now, click on the ‘Calculate Indices’ button to view the values of the six pollution indices defined earlier in Section I.

The program uses the data entered by the user to evaluate these indices and then displays the ‘Index Calculations’ window shown in Figure 85. The indices on the left-hand side are the indices based on the generation of potential environmental impacts, and the indices on the right-hand side are the indices based on the emission of impacts. These indices are calculated based on the equations in the page 13. Each index is accompanied by a Help button. Clicking on the ‘Help’ displays more information about that particular index at the bottom of the screen. The program also calculates the pollution index values for each of the individual streams. To see these values, click on the ‘Show WAR algorithm’ button. The program now displays the ‘Waste Reduction Algorithm’ window shown in Figure 86.



Indices based on Generation of Potential Environmental Impact

Total rate of Impact Generation
0.00154 Impact / Time

Specific Impact Generation
7.32168836231 Impact / Product

Rate of Generation of Pollutants per unit product
-1.1239599874 Mass Pollutants / Mass of products

Indices based on Emission of Potential Environmental Impact

Total rate of Impact Emission
0.00154 Impact / Time

Specific Impact Emission
7.32168836231 Impact / Product

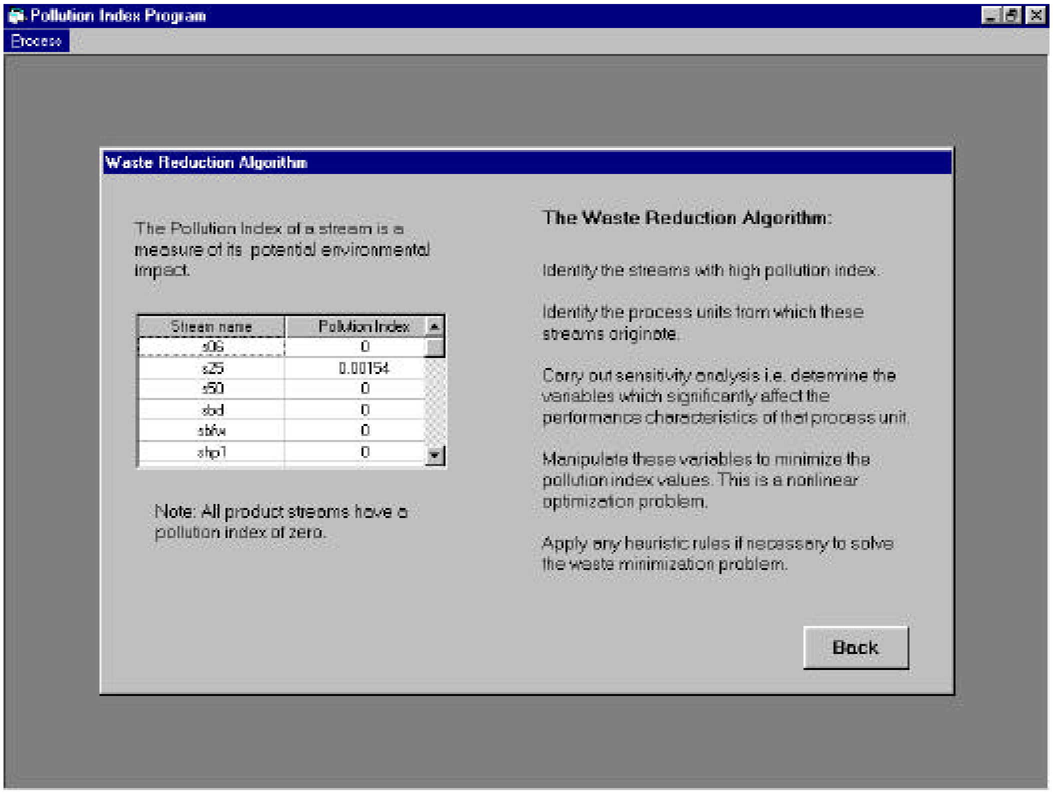
Rate of Emission of Pollutants per unit product
0.96879724628 Mass Pollutants / Mass of products

Help on the selected Index :

This index gives the potential environmental impact generated by the process for a unit mass of all the products. It is obtained by first calculating the total impact generation rate and then dividing it by the rate at which the process outputs products.

$$\hat{I}^{NP}_{gen} = \frac{\dot{I}^{NP}_{gen}}{\sum_{p} \dot{P}_{p}} = \frac{\dot{I}^{NP}_{out} - \dot{I}^{NP}_{in}}{\sum_{p} \dot{P}_{p}}$$

Figure 85 The Index Calculations Window



The Pollution Index of a stream is a measure of its potential environmental impact.

Stream name	Pollution Index
s06	0
s25	0.00154
s50	0
sbd	0
sbfw	0
shp1	0

Note: All product streams have a pollution index of zero.

The Waste Reduction Algorithm:

Identify the streams with high pollution index.

Identify the process units from which these streams originate.

Carry out sensitivity analysis i.e. determine the variables which significantly affect the performance characteristics of that process unit.

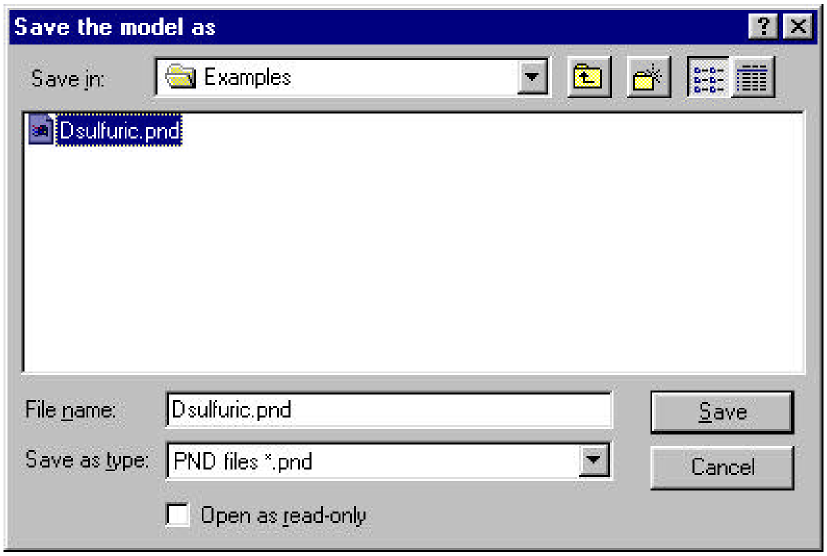
Manipulate these variables to minimize the pollution index values. This is a nonlinear optimization problem.

Apply any heuristic rules if necessary to solve the waste minimization problem.

Figure 86 The Waste Reduction Algorithm Window

In Figure 86 the table on the left-hand side shows the pollution index values for all the input and output streams in the contact process. A comparison of these values can help in identifying streams with high pollution content. In Figure 86 it can be seen that the pollution index values are zero for all the streams except stream s25, the stack gas. This shows that the stack gas stream is the main source of pollutant emission into the environment and needs special attention.

The right side of the 'Waste Reduction Algorithm' window shows the important steps of WAR algorithm, which gives a systematic way of approaching the waste minimization problem. The back button can be used to go back to the previous screens and make changes in the data. Click on the back button till you reach the process screen shown in Figure 81 Let us save the information entered so far by clicking on the 'save' button in the 'process' menu. The program displays the 'Save the model as' dialog box shown in Figure 87. The pollution index program stores the model as a file with '.pnd' extension. Let us save this model as 'Dsulfuric.pnd' in the Examples subdirectory of the program folder.



Save in: Examples

Dsulfuric.pnd

File name: Dsulfuric.pnd

Save as type: PND files *.pnd

☐ Open as read-only

Figure 87The Save As Window

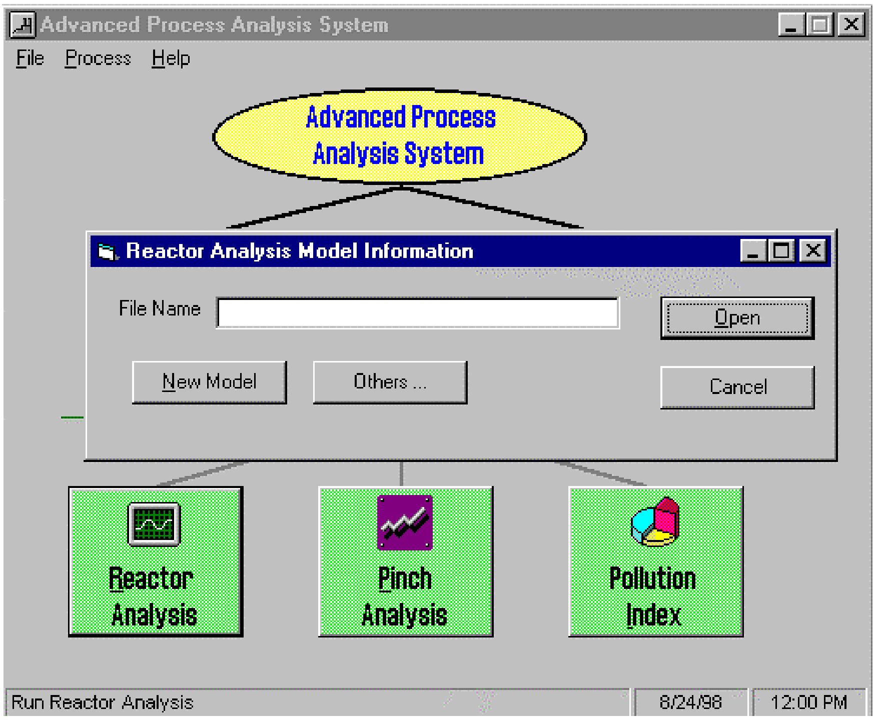
This concludes the implementation of the Pollution Index program in the Advanced Process Analysis System. Click the ‘Exit’ button in the process menu to return to the Advanced Process Analysis Desk. The next section explains the use of the Chemical Reactor Analysis program.

IX. USING CHEMICAL REACTOR ANALYSIS PROGRAM

The Reactor Analysis program was used to predict the performance of the packed bed catalytic reactors in the contact process. The chemical reactor program is an integral part of the Advanced Process Analysis System, and the reactor feed flowrates and compositions are provided to the program from the database. This section presents the screen images of the program with the contact process model. This will demonstrate how the reactor analysis program is integrated in the Advanced Process Analysis System.

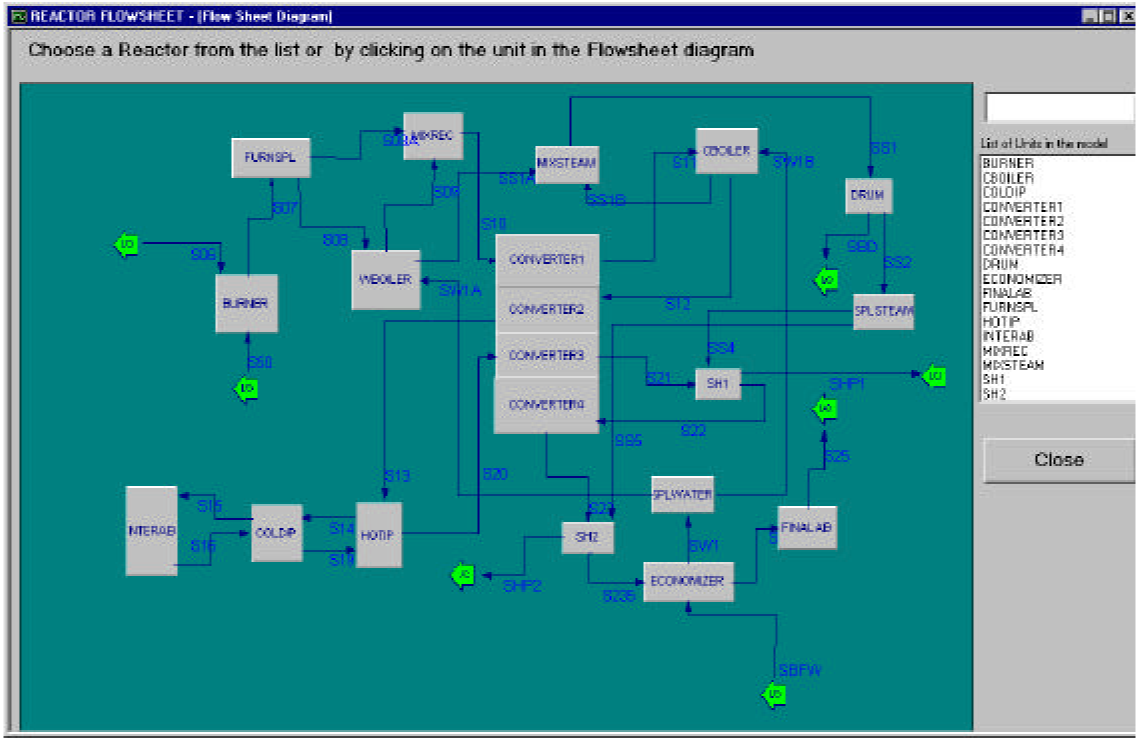
Upon clicking on the ‘Reactor Analysis’ button on the Advanced Process Analysis Desk shown in Figure 10, the ‘Reactor Analysis Model Information’ window is displayed. This window is shown in Figure 88.

Since we are using the Reactor Analysis program for the first time, click on the ‘New Model’ button . Once the ‘New Model’ button is clicked, the Flowsheet window of the Reactor Analysis program is displayed. This window is shown in Figure 89. The flowsheet diagram for the contact process model is shown in this window along with a list of units in the model. Choose the reactor unit by clicking on the unit in the flowsheet or from the list. Let us choose the first reactor bed in the model. The selected reactor unit name ‘Converter1’ appears in the text box. Clicking the ‘Close’ button closes this window and displays the Reactor Analysis Main window.



Run Reactor Analysis 8/24/98 12:00 PM

Figure 88:The Reactor Analysis Model Information Window



Choose a Reactor from the list or by clicking on the unit in the Flowsheet diagram

List of Units in the model

BURNER
CBOILER
COLDIP
CONVERTER1
CONVERTER2
CONVERTER3
CONVERTER4
DRUM
ECONOMIZER
FINALAB
FURNSPL
HOTIP
INTERAB
MIXREC
MIXSTEAM
SH1
SH2

Figure 89: Flowsheet Window

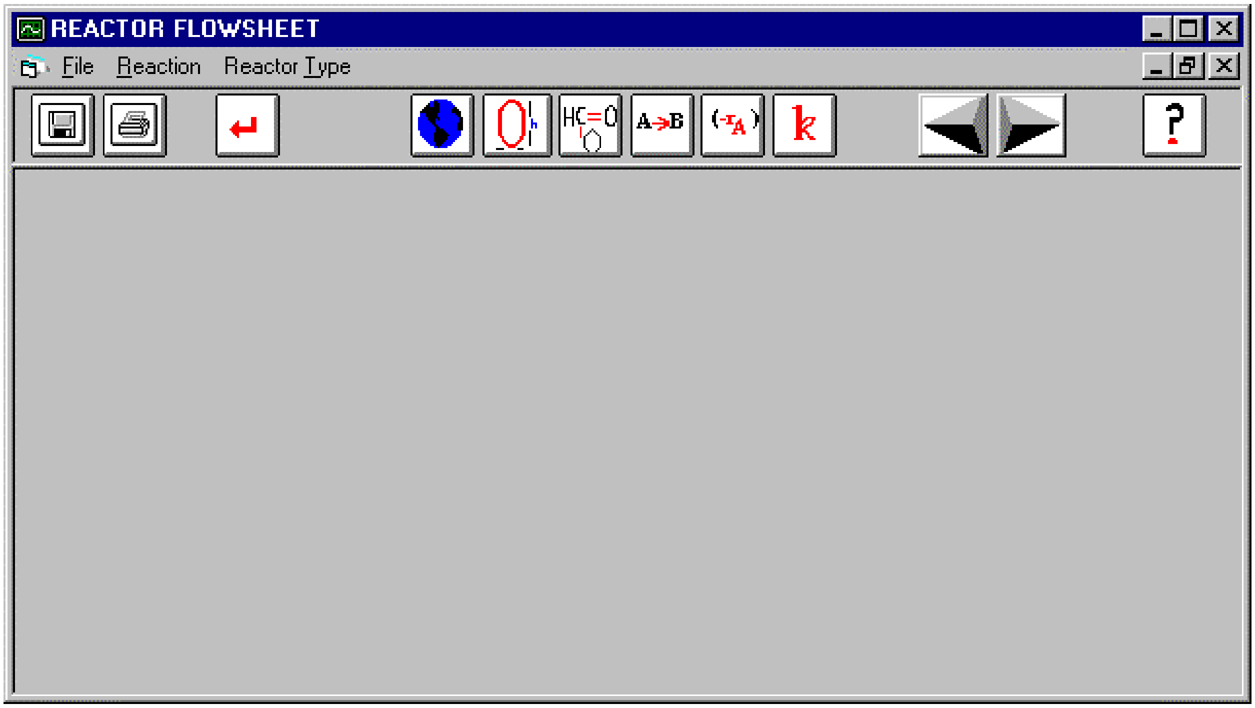


Figure 90: Main Window for Reactor Analysis

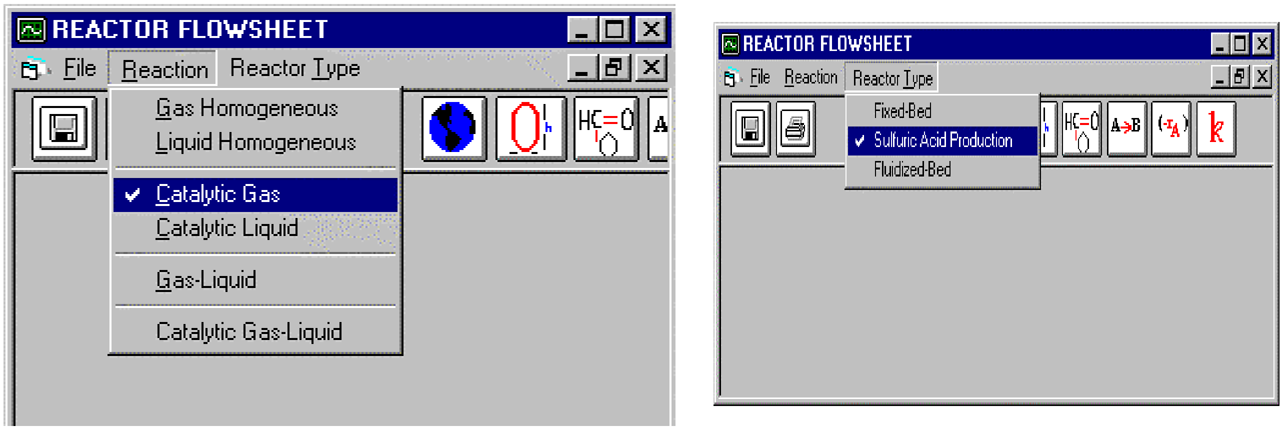
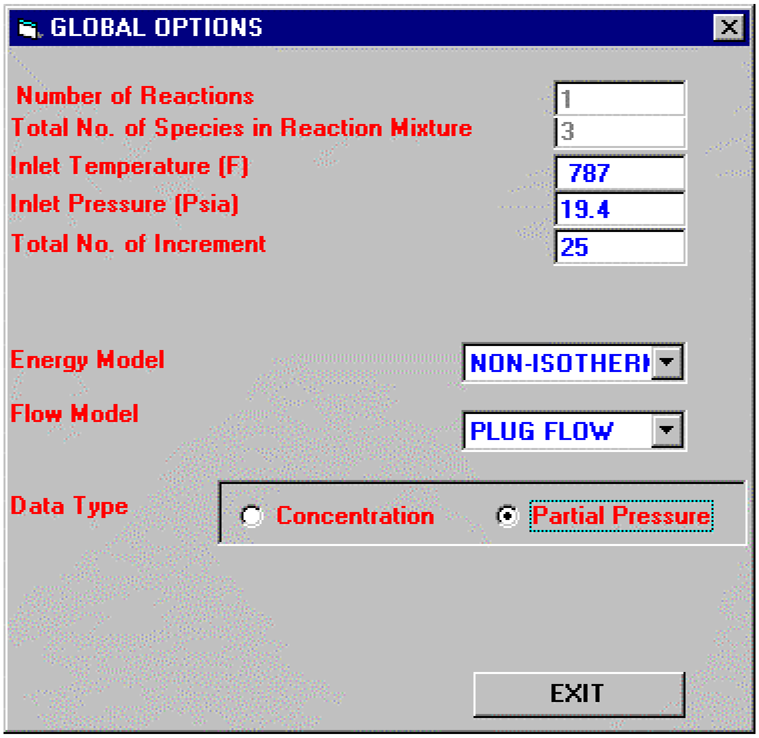


Figure 91: Reaction and Reactor Type Menus

The main window as shown in Figure 90 is displayed. The phase of the reaction should be selected from the ‘Reaction’ menu, which is shown in Figure 91. Let us choose ‘Catalytic Gas’ as the phase of the reaction. Next we have to choose the reactor type from the ‘Reactor Type’ menu which is shown in Figure 91. This is used to select the Reactor Type, The items of this menu depend upon the choice of reaction phase. For the contact process Let us choose ‘Sulfuric Acid Production’ as the type of reactor.



Number of Reactions: 1
Total No. of Species in Reaction Mixture: 3
Inlet Temperature (F): 787
Inlet Pressure (Psia): 19.4
Total No. of Increment: 25
Energy Model: NON-ISOTHERI
Flow Model: PLUG FLOW
Data Type: ○ Concentration ● Partial Pressure

Figure 92 : Global Options

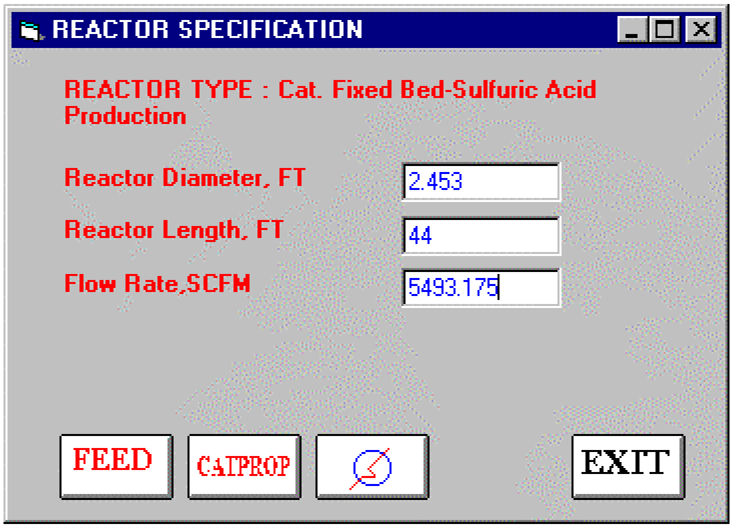
Let us proceed to enter the global options as shown in the Figure 92. Click on the 'Global Options' icon in the main window to open the Global Options window. Let us enter the number of reactions to be 1, the number of species to be 3, Inlet temperature to be 787 , Inlet pressure to be 19.4 and Total Number of Increments be 25.

Choose the Energy Model to be 'Non-Isothermal' from the list , choose Flow Model as "Plug Flow" and Data Type be "Partial Pressure" .Then click on the 'EXIT' button to close this window and return to the main window.

Let us proceed to the 'Reactant Specifications' step. Click on the "Reactant Specs" Icon to open Reactant Specifications window. Let us enter the Reactor Diameter to be 2.453, Reactor Length to be 44 and Flow Rate be 5493.175 as shown in Figure 93.

Press the "FEED" button in Reactor Specification window to enter the components partial pressures . This screen is shown in Figure 94 . Let us enter the values for A as 11.08 , for B as 7.9586 and for C as 0.362 . Then press "EXIT " button to close the Feed Window.

Press "CATPROP" button on the Reactant Specifications Window to enter the Catalyst properties for Reactor Analysis . This opens the screen shown in Figure 95 . Let us enter the catalyst density ,catalyst diameter, bed voidage as 33.8 ,0.0405, and 0.45 respectively as shown in Figure 95 . Let the type be LP-110.



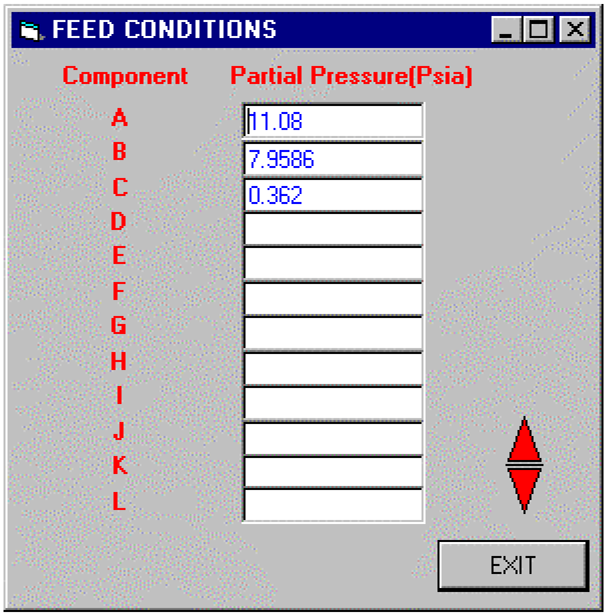
REACTOR TYPE : Cat. Fixed Bed-Sulfuric Acid Production

Reactor Diameter, FT: 2.453

Reactor Length, FT: 44

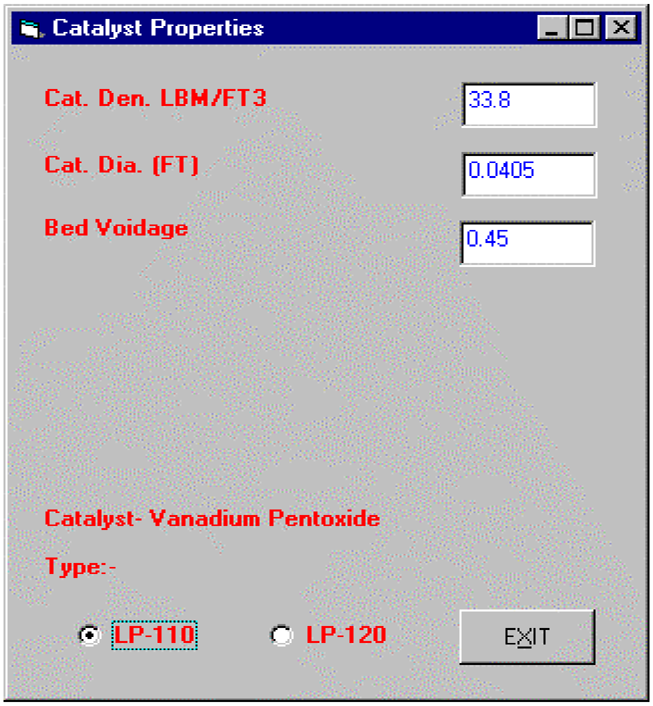
Flow Rate,SCFM: 5493.175

Figure 93: Reactor Specifications



Component	Partial Pressure(Psia)
A	11.08
B	7.9586
C	0.362
D	
E	
F	
G	
H	
I	
J	
K	
L	

Figure 94: Feed Conditions



Cat. Den. LBM/FT3: 33.8

Cat. Dia. (FT): 0.0405

Bed Voidage: 0.45

Catalyst- Vanadium Pentoxide

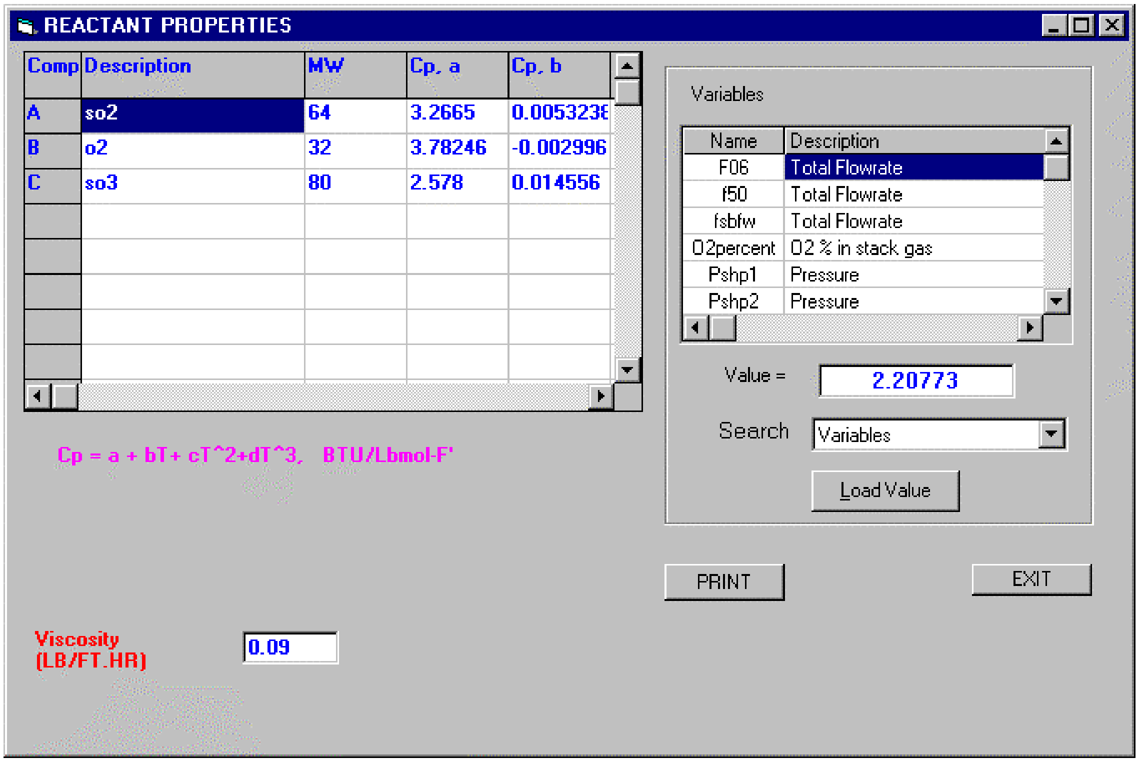
Type:-

● LP-110 ○ LP-120

Figure 95: Catalyst Properties

Click on the ‘Reactants’ icon on the toolbar of the main window to open the Reactant Properties window. There are three components in the reacting gases of Converter 1. These are sulfur dioxide, oxygen and sulfur trioxide. All of these components with their molecular weights and their heat capacity coefficients are retrieved from the database.

The table ‘Variables’ on the right-hand side shows the list of all the measured and unmeasured variables in the contact process model. The value corresponding to the selected variable is shown in below the table. Similarly, the list of parameters and constants in the model can be viewed by choosing ‘Parameters’ and ‘Constants’ respectively from the list. The values of the selected variables can be loaded as molecular weight or the heat capacities of a particular species from the database.



Comp	Description	MW	Cp, a	Cp, b
A	so2	64	3.2665	0.005323
B	o2	32	3.78246	-0.002996
C	so3	80	2.578	0.014556

Cp = a + bT+ cT^2+dT^3, BTU/Lbmol-F'

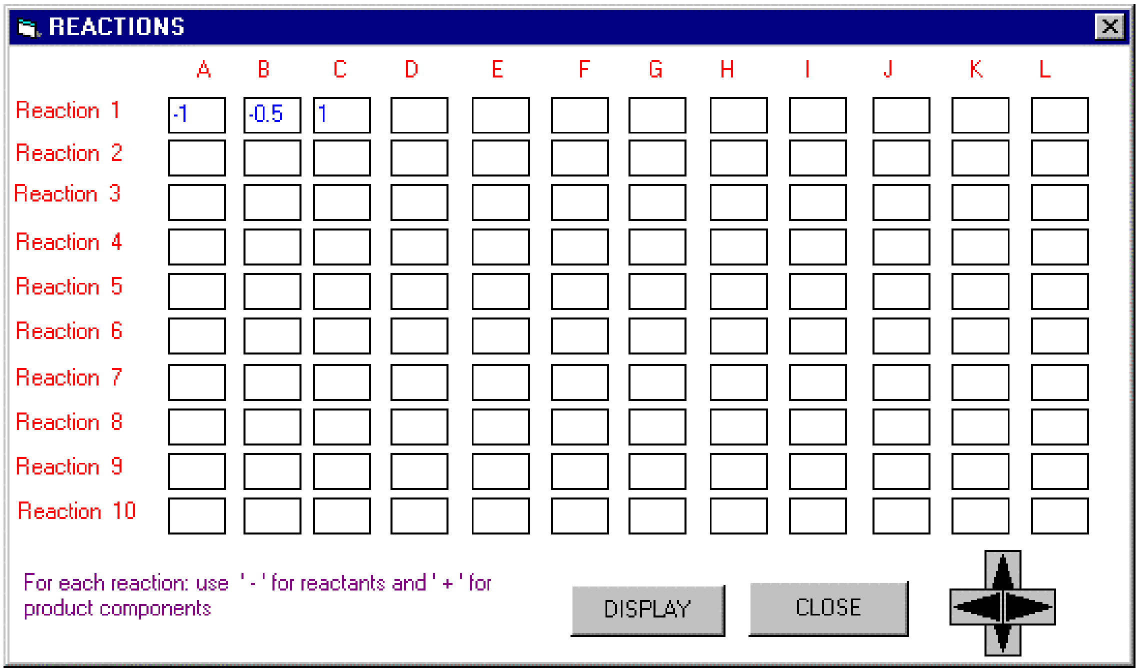
Name	Description
F06	Total Flowrate
f50	Total Flowrate
fsbfw	Total Flowrate
O2percent	O2 % in stack gas
Pshp1	Pressure
Pshp2	Pressure

Value = 2.20773

Search: Variables

Viscosity (LB/FT.HR): 0.09

Figure 96: Reactant Properties Window



	A	B	C	D	E	F	G	H	I	J	K	L
Reaction 1	-1	-0.5	1									
Reaction 2												
Reaction 3												
Reaction 4												
Reaction 5												
Reaction 6												
Reaction 7												
Reaction 8												
Reaction 9												
Reaction 10												

For each reaction: use ' - ' for reactants and ' + ' for product components

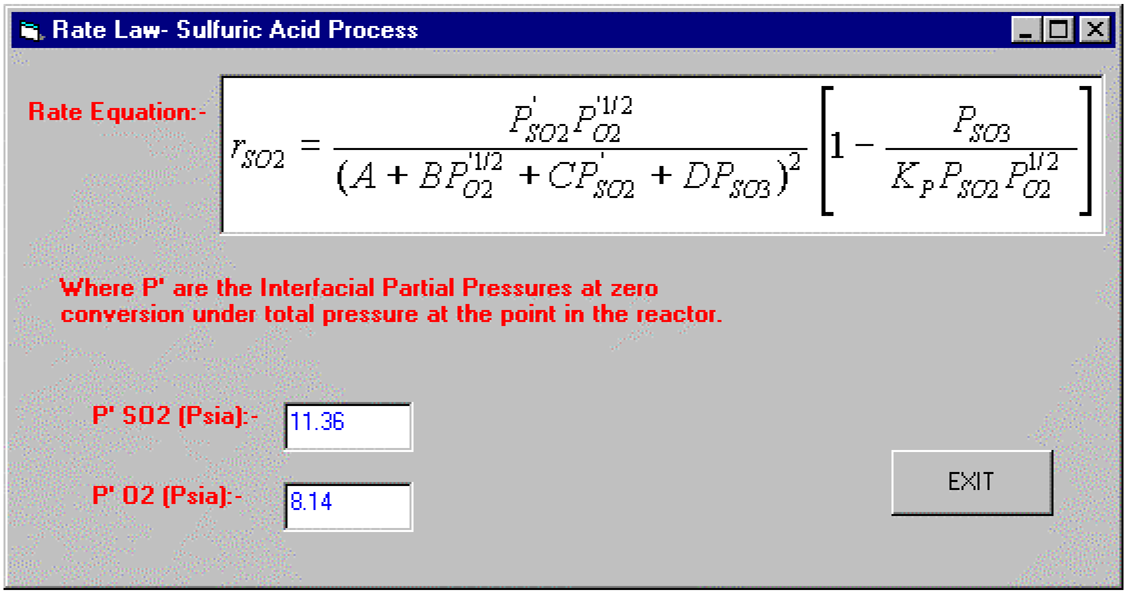
Figure 97: Stoichiometry Window

Clicking on the ‘Stoichiometry’ icon in the toolbar of the main window shown in Figure 90 opens the Stoichiometry window. The Stoichiometry window is shown in Figure 97. The reaction stoichiometric coefficients can be entered in this window.

A negative stoichiometric coefficient indicates that this component is acting as a reactant species for current reaction, while a positive coefficient indicates a reaction product. In Figure 97, the coefficient for A (SO_2) is -1, the coefficient for B (O_2) is -0.5 and the coefficient of C (SO_3) is 1.

Return to the main window,Figure 90,and Proceed to the “rate“ window . The window displayed is the ‘Reaction Rate’ window. This is shown in Figure 98 . It shows the rate equation for Contact Process.

Return to the main window Figure 90 , and by clicking on “Run” in the tool bar. The total reactor length will be divided bythe number of increments and the calculations will be performed for each increment. The results will be displayed graphically as shown in Figure 99.



Rate Equation:-

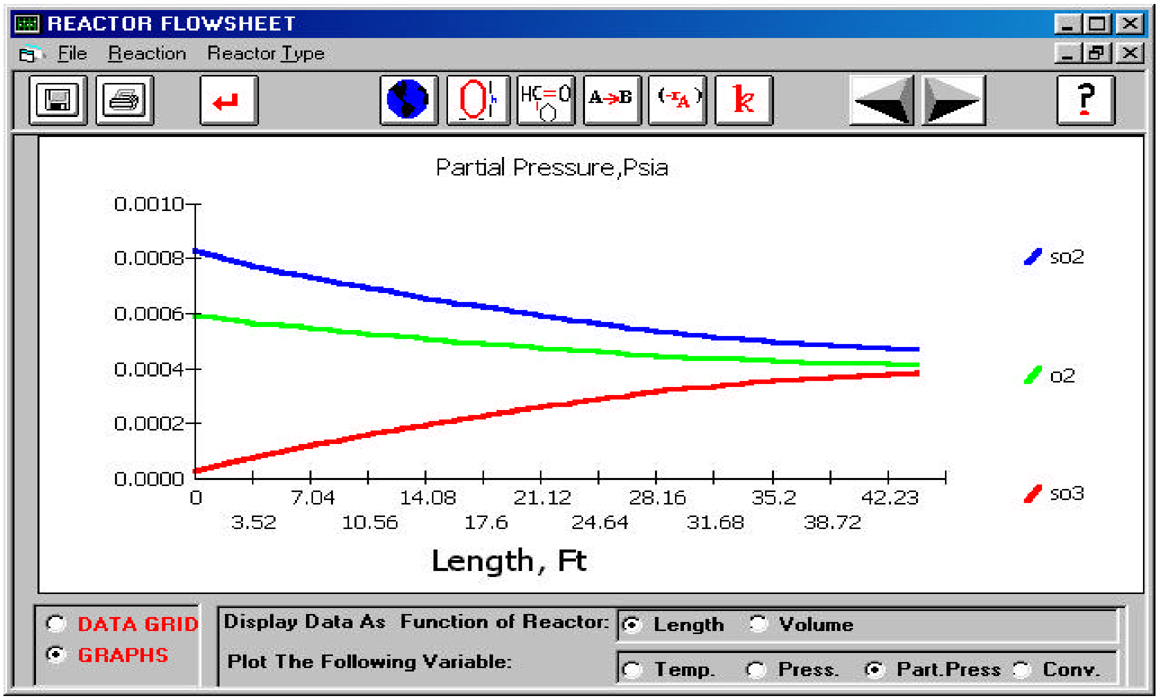
$$r_{SO2} = \frac{P'_{SO2} P'^{1/2}_{O2}}{(A + BP'^{1/2}_{O2} + CP'_{SO2} + DP_{SO3})^2} \left[1 - \frac{P_{SO3}}{K_P P_{SO2} P^{1/2}_{O2}} \right]$$

Where P' are the Interfacial Partial Pressures at zero conversion under total pressure at the point in the reactor.

P' SO2 (Psia):- 11.36

P' O2 (Psia):- 8.14

Figure 98 The Reaction Rate Window

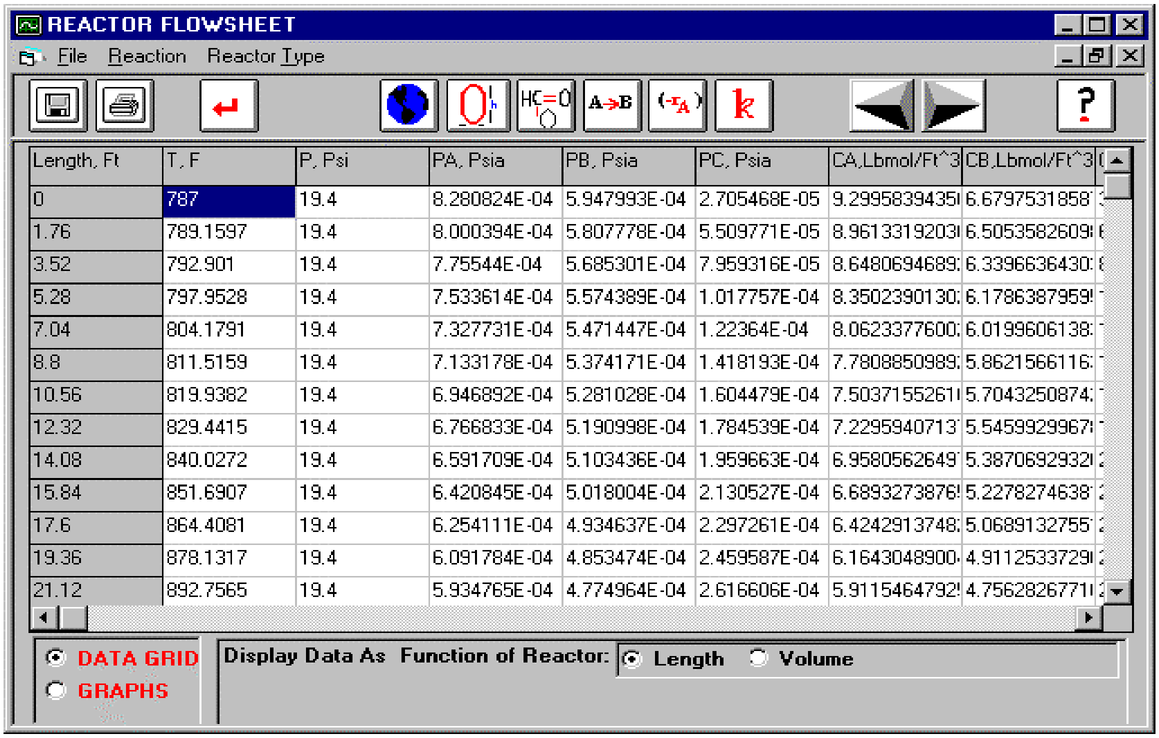


○ DATA GRID
● GRAPHS

Display Data As Function of Reactor: ● Length ○ Volume

Plot The Following Variable: ○ Temp. ○ Press. ● Part.Press ○ Conv.

Figure 99: Results in the Graphical Form



Length, Ft	T, F	P, Psi	PA, Psia	PB, Psia	PC, Psia	CA,Lbmol/Ft^3	CB,Lbmol/Ft^3
0	787	19.4	8.280824E-04	5.947993E-04	2.705468E-05	9.2995839435	6.6797531858
1.76	789.1597	19.4	8.000394E-04	5.807778E-04	5.509771E-05	8.9613319203	6.5053582609
3.52	792.901	19.4	7.75544E-04	5.685301E-04	7.959316E-05	8.6480694689	6.3396636430
5.28	797.9528	19.4	7.533614E-04	5.574389E-04	1.017757E-04	8.3502390130	6.1786387959
7.04	804.1791	19.4	7.327731E-04	5.471447E-04	1.22364E-04	8.0623377600	6.0199606138
8.8	811.5159	19.4	7.133178E-04	5.374171E-04	1.418193E-04	7.7808850989	5.8621566116
10.56	819.9382	19.4	6.946892E-04	5.281028E-04	1.604479E-04	7.5037155261	5.7043250874
12.32	829.4415	19.4	6.766833E-04	5.190998E-04	1.784539E-04	7.2295940713	5.5459929967
14.08	840.0272	19.4	6.591709E-04	5.103436E-04	1.959663E-04	6.9580562649	5.3870692932
15.84	851.6907	19.4	6.420845E-04	5.018004E-04	2.130527E-04	6.6893273876	5.2278274638
17.6	864.4081	19.4	6.254111E-04	4.934637E-04	2.297261E-04	6.4242913748	5.0689132755
19.36	878.1317	19.4	6.091784E-04	4.853474E-04	2.459587E-04	6.1643048900	4.9112533729
21.12	892.7565	19.4	5.934765E-04	4.774964E-04	2.616606E-04	5.9115464792	4.7562826771

● DATA GRID
○ GRAPHS

Display Data As Function of Reactor: ● Length ○ Volume

Figure 100: Reactor Analysis Results in tabular Form

Figure 99 shows the graph plotted with the concentration versus length of the reactor. Similarly the graph could be plotted for temperature, pressure, concentration or conversion versus length or volume.

The results can also be viewed by in a tabular form by clicking on the 'Data Grid' option provided in the left bottom corner of the main window. The results in the tabular form are shown in Figure 100. The data can be displayed as a function of reactor length and volume.

Save the file as a '**.REC**' file using the 'Save As' option in the File menu of the main window shown in Figure 90. **Exit** the program by clicking n the '**End**' option in the File menu of the main window. This conclude the reactor analysis.

X. Results from Applying the Advanced Process Analysis System to the Contact Process

This section describes the results from applying the Advanced Process Analysis System to the contact process. This process is a mature technology and only small increments of improvements are obtained, but the important result is demonstrating the capability of the system on an actual process.

***Process Description* :**

The IMC Agrico contact plant in Convent, Louisiana was built by the Chemical Concentration Company in 1966. It produces 4800 TPD 93%(wt) sulfuric acid and process steam as a by-product, and it has a Bailey INFI 90 distributed control system. This process incorporates packed bed catalytic reactors, absorption towers and heat exchanger networks, among others. A detailed description of the process is given by Telang (1988).

Process Model:

An open form model was developed from the process flow diagram and process design data. The packed bed catalytic reactor was simulated with a kinetic model given by Chen (1998). The process model has 43 measured variables, 732 unmeasured variables, 11 parameters and 761 linear and nonlinear equality constraints. The model equations were entered in the flowsheeting program, and a comparison of results from the process model with the plant design data was made to assess the validity and accuracy of the simulation. The simulation matched the plant design data within the accuracy of the data. Also, a comparison was made with process data taken from the plant operating five years after start-up, and the simulation with parameters updated with reconciled plant data agreed within the accuracy of the data, e.g. outlet temperatures from the packed bed reactors agreeing within 3EF. Details of these comparisons are given by Chen (1998).

On-Line Optimization:

Two sets of plant data from DCS were used to evaluate on-line optimization of the contact process, and the details of these optimal solutions are reported by Chen (1998). Six measurements of the total of 43 were detected as containing gross errors using the contaminated Gaussian function option. These were four temperatures, a flow rate and composition, and they were caused by incorrectly calibrated instruments. These values were replaced by reconciled data, and the simultaneous data reconciliation and parameter estimation program was executed. Then the updated parameters were used in the plant model for economic optimization to obtain the optimal set points. Economic optimization gave an increased profit of 3.0% (or $350,000/ year) and a 10% reduction in sulfur dioxide emissions over current operating condition. This is consistent with other reported applications of on-line optimization and could lead to a typical return on investment of one year.

Chemical Reactor Analysis :

The process has four packed bed catalytic reactors that use two different types of vanadium pentoxide catalyst to convert sulfur dioxide to sulfur trioxide. This reaction is exothermic and equilibrium is approached exiting each bed. Heat is removed to shift the equilibrium, and this heat is used to produce steam. Also, the equilibrium conversion is increased the fourth catalyst bed by removing $SO_{3.}$ in the inter-pass absorption tower. A detailed description of the kinetic model is give by Chen (1998), and it includes an intrinsic reaction rate, pore diffusion temperature gradient between the gas and pellet, and reversible reaction using the equilibrium constant. The kinetic model was entered in the chemical reactor analysis, and an evaluation of the effect of reactor pressure on conversion was made. This showed that the conversion could be increased by 19% in the first reactor and the volume could be decreased by 87% by using a reactor pressure of 10.3 atms. rather than the current operations at 1.3 atms.

Pinch Analysis :

The heat exchanger network program was used to apply pinch analysis to the contact process This process is a highly exothermic, and heat released from combustion of sulfur and conversion of sulfur dioxide to sulfur trioxide is used to produce steam which is a valuable product. The process was determined to be below the pinch, and no hot utility was required. The minimum amount of cold utility was 3.703×10^8 KJ /hr. A proposed heat exchanger network has thirteen heat exchangers with a total area of 25% less than the current one. The results showed that the existing process is not using any excess utilities, and the energy efficiency can not be improved. However, the network solution provided by the program has less area than the existing network. This shows that the program can be used to check the optimality of existing networks and develop better designs.

Pollution Indices :

The pollution index part of the system was used to demonstrate the pollution prevention analysis with the contact process. The pollution indices were calculated for the process, and the results indicated that the stack gas was the primary pollution impact from the process. The sulfur furnace and the converter were identified as the candidates for process modification. Thus, the pollution index program can be used to evaluate the environmental efficiency of a plant and assist in making decisions regarding process improvement

Conclusions

An advanced process analysis system has been developed to perform comprehensive evaluations on chemical and refinery processes for waste minimization. With this system, process engineers can use programs interactively and simultaneously for on-line optimization, chemical reactor analysis, flowsheeting, pinch analysis and pollution indices. Results from applying the system to a IMC Agrico/Chemical Concentration Company contact process for sulfuric acid demonstrate the applicability of the system for process improvement and pollution prevention.

X. OPTIMIZATION SOLVER-GAMS

A. Compilation Output (Brooke, et al., 1996)

The compilation output is produced during the initial check of the program, and it is often referred to as a compilation. It includes two or three parts: the echo print of the program, an explanation of any errors detected, and the symbol reference maps. The echo print of the program is always the first part of the output file. If errors had been detected, the explanatory messages would be found at the end of the echo print. The echo print of the GAMS program for the economic optimization of the contact process is included in the GAMS output file in Appendix B.

The symbol reference maps follow the echo print, and they include the symbol cross-reference and the symbol-listing map. These are extremely useful if one is looking into a model written by someone else, or if one is trying to make some changes in their own model after spending time away from it. The symbol cross reference lists the identifiers (symbols) in the model in alphabetical order, identifies their type, shows the line numbers where the symbols appear, and classifies each appearance. The complete list of data types is given in Table 8. Next in the listing is a list of references to the symbols, grouped by reference type and identified by the line number in the output file. The actual references can then be found by referring to the echo print of the program, which has line numbers on it. The complete list of reference types is given in Table 9. The symbol reference maps do not appear in the output files by default. However, it can be included in the output files by changing the default setting in Output File Format Specification window.

Table 8 A List of Data Types

Entry in symbol reference table	GAMS data type
SET	set
PARAM	parameter
VAR	variable
EQU	equation
MODEL	model

B. Execution Output

The execution output follows the compilation output and is also found in the GAMS output file. If a display statement is present in the GAMS program, then data requested by the display statement is produced in the execution output while GAMS performs data manipulations. Also, if errors are detected because of illegal data operations, a brief message indicating the cause and the line number of the offending statement, will appear in the execution output. The execution output will be shown in the GAMS output file if a display statement is present in the GAMS program (which requests the display of the value of a variable) or if an execution error is encountered.

Table 9 A List of Reference Types

Reference	Description
DECLARED	This is where the identifier is declared as to type. This must be the first appearance of the identifier.
DEFINED	This is the line number where an initialization (a table or a data list between slashes) or symbol definition (equation) starts for the symbol.
ASSIGNED	This is when values are replaced because the identifier appears on the left of an assignment statement.
IMPL-ASN	This is an "implicit assignment": an equation or variable will be updated as a result of being referred to implicitly in a solve statement.
CONTROL	This refers to the use of a set as the driving index in an assignment, equation, loop or other indexed operation (sum, prod, smin or smax).
REF	This is a reference: the symbol has been referenced on the right of an assignment in a display, in an equation, or in a model or solve statement.

C. Output produced by a Solve Statement (Brooke, et al., 1996)

The output triggered by a solve statement includes the equation listing, the column listing, the model statistics, solver report, the solution listing, report summary, and file summary as shown in the GAMS output file in Section X. All of the output produced as a result of a SOLVE statement is labeled with a subtitle identifying the model, its type, and the line number of the solve statement.

The first list in the output produced by the SOLVE statement is the Equation Listing, which is marked with that subtitle in the output file. The Equation Listing is an extremely useful debugging aid. It shows the variables that appear in each constraint, and what the individual coefficients and right-hand-side value evaluate to after the data manipulations have been made. Normally, the first three equations in every block are listed. Most of the listing is self-explanatory. The name, text, and type of constraints are shown. The four dashes are useful for mechanical searching. All terms that depend on variables are collected on the left, and all the constant terms are combined into one number on the right, with any necessary sign changes made. For example, a equation "x + 5y - 10z +20 =e= 0" is rearranged as: "x + 5y - 10z =e= -20". Four places of decimals are shown if necessary, but trailing zeroes following the decimal point are suppressed. E-format is used to prevent small numbers being displayed as zero. By default, the equation listing will not appear in the output file unless specified by the user in the Output File Format Specification Window.

The general format in the equation listing was described above. However, the nonlinear terms in an equation are treated differently from the linear terms. If the coefficient of a variable in the Equation Listing is enclosed in parentheses, then the variable corresponding to this coefficient is nonlinear in the constraint equation, and the value of the coefficient depends on the activity levels of one or more of the variables. This coefficient is not algebraic, but it is the partial derivative of each variable evaluated at their current level values (initial points).

For an equation: $x + 2y^3 + 10$ =e= 0 with current level values $x = 2$ and $y = 1$, this equation is listed in the equation listing as: x + (6) y =e= -12, where the coefficient of y is the partial derivative of the equation with respect to y evaluated at y=1, i.e., $6y^2 = 6$. The right hand side coefficient, -12, is the sum of constant in the equation, 10, and the constant, 2, from the linearization of the nonlinear term $2y^3$ using Taylor expansion evaluated at $y = 1$. x in this equation is linear, and its coefficient is shown as 1 without the parentheses.

Next, the column listing gives the individual coefficients sorted by column rather than by row. The default shows the first three entries for each variable, along with their bound and level values. The format for the coefficients is the same as in the equation listing, with the nonlinear ones enclosed in parentheses and the trailing zeroes dropped. The order in which the variables appear is the order in which they were declared.

The final information generated while a model is being prepared for solution is the statistics block to provide details on the size and nonlinearity of the model. The status for the solver (the state of the program) and the model (what the solution looks like) are characterized in solver status and model status. The model status and solver status are listed in Table 10 and Table 11, respectively.

The next section is the solver report, which is the solve summary particular to the solver program that has been used. Also, there will be diagnostic messages in plain language if anything unusual was detected, and specific performance details as well. In case of serious trouble, the GAMS listing file will contain additional messages printed by the solver, which may help, identify the cause of the difficulty.

Solution listing is a row-by-row then column-by-column listing of the solutions returned to GAMS by the solver program. Each individual equation and variable is listed with four pieces of information. The four columns associated with each entry are listed in Table 12. For variables, the values in the LOWER and UPPER columns refer to the lower and upper bounds. For equations, they are obtained from the (constant) right-hand-side value and from the relational type of the equation. EPS means very small or close to zero. It is used with non-basic variables whose marginal values are very close to, or actually, zero, or in nonlinear problems with superbasic variables whose marginal values are zero or very close to it. A superbasic variable is the one between its bounds at the final point but not in the basis.

For models that do not reach an optimal solution, some constraints may be marked with the flags shown in Table 13. The final part of solution listing is the report summary marked with four asterisks. It shows the count of rows or columns that have been marked INFES, NOPT, UNBND. The sum of infeasibilities will be shown if the reported solution is infeasible. The error count is only shown if the problem is nonlinear. The last piece of the output file is the file summary, which gives the names of the input and output disk files. If work files have been used, they will be named here as well.

D. Error Reporting

The last part in the output file is error reporting. All the comments and descriptions about errors have been collected into this section for easy reference. Errors are grouped into the three phases of GAMS modeling in the on-line optimization system: compilation, execution and model generation (which includes the solution that follows). They will be illustrated in the section, "Error Reporting".

Table 10 A List of Model Status in GAMS Output Files

Model status	Meaning
1. Optimal	This means that the solution is optimal. It only applies to linear problems or relaxed mixed integer problems (RMIP).
2. Locally Optimal	This message means that a local optimal for nonlinear problems, since all that can guarantee for general nonlinear problems is a local optimum.
3. Unbounded	That means that the solution is unbounded. It is reliable if the problem is linear, but occasionally it appears for difficult nonlinear problem that lack some strategically paced bounds to limit the variables to sensible values.
4. Infeasible	This means that he linear problem is infeasible.
5. Locally Infeasible	This message means that no feasible point could be found for the nonlinear problem from the given starting point. It does not necessarily mean that no feasible point exists.
6. Intermediate Infeasible	The current solution is not feasible, the solver program stopped, either because of a limit (iteration or resource), or some sort of difficulty.
7. Intermediate Nonoptimal	This is again an incomplete solution, but it appears to be feasible.
8. Integer Solution	An integer solution has been found to a MIP (mixed integer problem).
9. Intermediate Noninteger	This is an incomplete solution to a MIP. An integer solution has not yet been found.
10. Integer	There is no integer solution to a MIP. This message should be reliable.
11.Error Unknown, Error no Solution	There is no solution in either of these cases.

Table 11 A List of Solver Status in GAMS Output Files

Solver status	Meaning
1. Normal Completion	This means that the solver terminated in a normal way: i.e., it was not interrupted by an iteration or resource limit or by internal difficulties. The model status describes the characteristics of the accompanying solution.
2. Iteration Interrupt	This means that the solver was interrupted because it used too many iterations. Use option iterlim to increase the iteration limit if everything seems normal.
3. Resource Interrupt	This means that the solver was interrupted because it used too much time. Use option reslim to increase the time limit if everything seems normal.
4. Terminated by Solver	This means that the solver encountered difficulty and was unable to continue. More detail will appear following the message.
5. Evaluation Error Limit	Too many evaluations of nonlinear terms at undefined values. You should use bounds to prevent forbidden operations, such as division by zero. The rows in which the errors occur are listed just before the solution.
6. Unknown Error Preprocessor(s) Error Setup Failure Error Solver Failure Error Internal Solver Error Error Post-Processor	All these messages announce some sort of unanticipated failure of GAMS, a solver, or between the two. Check the output thoroughly for hints as to what might have gone wrong.

Table 12 A List of Solution Listing Types

Heading in listing file	Description
LOWER	Lower Bound (.lo)
LEVEL	Level Value (.l)
UPPER	Upper Bound (.up)
MARGINAL	Marginal (.m)

Table 13 A List of Constraint Flags

Flag	Description
INFES	The row or column is infeasible. This mark is make for any entry whose LEVEL value is not between the UPPER and LOWER bounds.
NOPT	The row or column is non-optimal. This mark is made for any non-basic entries for which the marginal sign is incorrect, or superbasic ones for which the marginal value is too large.
UNBND	The row or column that appears to cause the problem to be unbounded.

E. GAMS Input Model (Brooke et al., 1996)

The basic components of a GAMS input model include:

- Sets
- Data (Parameters, Tables, Scalar)
- Variables
- Assignment of bounds and/or initial values
- Equations
- Model and Solve statements
- Display/Put statement

The overall content of GAMS output file is:

- Echo Print
- Reference Maps
- Equation Listings
- Status Reports
- Results

E-1. Format for Entering System Information

The GAMS input code generated by the interactive on-line optimization system is based on the information provided by the user. Although the user usually does not need to consider the format of the GAMS program, there are some regulations about the format related to GAMS that must be followed to properly enter information about the plant. The input must be in correct format for an accurate GAMS input file to be generated automatically by the on-line optimization system.

Most of the characters and words are allowable for the input information, however, the letters in the input information are case insensitive. A few characters are not allowed for the input because they are illegal or ambiguous on some machines. Generally, all unprintable and control characters are illegal. Most of the uncommon punctuation characters are not part of the language, but can be used freely. In Table 14, a full list of legal characters is given.

Besides characters, there are some reserved words and non-alphanumeric symbols with predefined meanings in GAMS, which can not be used, in input information. The reserved words and non-alphanumeric symbols are listed in Table 15 and Table 16, respectively.

Table 14 A List of Full Set of Legal Characters for GAMS

A to Z	alphabet	a to z	alphabet	0 to 9	Numerals
&	ampersand	“ ”	double quote	#	pound sign
*	asterisk	=	equals	?	question mark
@	at	>	greater than	;	semicolon
\	back slash	<	less than	‘	single quote
:	Colon	-	minus	/	slash
,	comma	( )	parenthesis		space
$	Dollar	[ ]	square brackets	_	underscore
.	Dot	{ }	braces	!	exclamation mark
+	Plus	%	percent	^	circumflex

Table 15 A List of All Reserved Words for GAMS

abort	ge	Not	smin	if
acronym	gt	Option	sos1	then
acronyms	inf	Options	sos2	else
alias	integer	Or	sum	semicont
all	le	Ord	system	semiint
and	loop	Parameter	table	file
assign	lt	Parameters	using	files
binary	maximizing	Positive	variable	putpage
card	minimizing	Prod	variables	puttl
display	model	Scalar	xor	free
eps	models	Scalars	yes	no
eq	na	Set	repeat	solve
equation	ne	Sets	until	for
equations	Negative	Smax	while	

In the on-line optimization system, numeric values are entered in a style similar to that used in other computer languages. Blanks cannot be used in a number because the system treats a blank as a separator. The common distinction between real and integer data types does not exist. If a number is entered without a decimal point, it is still stored as a real number. In addition, the system uses an extended range arithmetic that contains special symbols for infinity (INF), negative infinity (-INF), undefined (UNDF), epsilon (EPS), and not available (NA) as shown in Table 17. One cannot enter UNDF; it is only produced by an operation that does not have a proper result, such as division by zero. All other special symbols can be entered and used as if they were ordinary numbers.

Table 16 A List of Non-alphanumeric Symbols for GAMS

=l=	--
=g=	++
=e=	**
=n=	

GAMS uses a small range of numbers to ensure that the system will behave in the same way on a wide variety of machines. A general rule is to avoid using or creating numbers with absolute values greater than 1.0e+20. A number up to 10 significant digits can be entered on all machines, and some machines can even support more than that. However, if a number is too large, it may be treated by the system as undefined (UNDF), and all values derived from it in a model may be unusable. It is recommended to always use INF (or -INF) explicitly for arbitrarily large numbers. When an attempted arithmetic operation is illegal or has undefined results because of the value of arguments (division by zero is the normal example), an error is reported and the result is set to undefined (UNDF). Afterwards, UNDF is treated as a proper data value and does not trigger any additional error messages. Thus, the system will not solve a model if an error has been detected, but it will terminate with an error condition.

The string definition such as the variable's name in the system has to start with a letter followed by more letters or digits. It can only contain alphanumeric characters and up to 10 characters long. The comment to describe the set or element must not exceed 80 characters. Basically, there are five possible types of variables that may be used which are listed in Table 18.

The type of mathematical programming problem must be known before the problem is solved. The on-line optimization system can only solve linear and nonlinear optimization problems. However, GAMS can solve a large number of optimization problems, which are summarized in Table 19.

As the interactive on-line optimization system writes all the required GAMS input files for the user, most of the components in the GAMS input model are automatically formulated from the information provided in the input windows. If the user can follow the explicit rules introduced above, the GAMS input file can be generated automatically. After the user enters all the plant information through the input windows, the GAMS source codes will be generated.

Table 17 A List of Special Symbols for GAMS

Special symbol	Description
INF	Plus infinity. A very large positive number
-INF	Minus infinity. A very large negative number
NA	Not available. Used for missing data. Any operation that uses the value NA will produce the result NA
UNDF	Undefined. The result of an undefined or illegal operation. The user cannot directly set a value to UNDF
EPS	Very close to zero, but different from zero.

Table 18 A List of Types of Variables for GAMS

Keyword	Default Lower Bound	Default Upper Bound	Description
Free (default)	-inf	+inf	No bounds on variables. Both bounds can be changed from the default values by the user
Positive	0	+inf	No negative values are allowed for variables. The upper bound can be changed from the default value by the user
Negative	-inf	0	No positive values are allowed for variables. The user can change the lower bound from the default value.
Binary	0	1	Discrete variable that can only take values of 0 or 1
Integer	0	100	D Discrete variable that can only take integer values between the bounds. Bounds can be changed from the default value by the user

The on-line optimization system will then forward these source codes to the GAMS software. This initiates the execution of GAMS and also creates output files so the user can view the execution in the output window. The execution and the output has been discussed in the previous sections.

Table 19 A List of Types of Models for GAMS

Model Type	Description
LP	Linear programming. No nonlinear terms or discrete (binary or integer) variables.
NLP	Nonlinear programming. There are general nonlinear terms involving only “smooth” functions in the model, but no discrete variables.
DNLP	Nonlinear programming with discontinuous derivatives. Same as NLP, but “non-smooth” functions can appear as well. More difficult to solve than NLP. Not recommended to use.
RMIP	Relaxed mixed integer programming. Can contain discrete variables but the integer and binary variables can be any values between their bounds.
MIP	Mixed integer programming. Like RMIP but the discrete requirements are enforced: the discrete variables must assume integer values between their bounds.
RMINLP	Relaxed mixed integer nonlinear programming. Can contain both discrete variables and general nonlinear terms. The discrete requirements are relaxed. Same difficulty as NLP.
MINLP	Mixed integer nonlinear programming. Characteristics are the same as for RMINLP, but the discrete requirements are enforced.
MCP	Mixed Complementarily Problem
CNS	Constrained Nonlinear System

E-2. Equation Formulation

Besides the rules introduced above, the equations as the main part of the input information have their own specific requirements. The mathematical definitions of equations can be written in one or multiple lines. Blanks can be inserted to improve readability, and expressions can be arbitrarily complicated. The standard arithmetic operations for the equations are listed in Table 20. The arithmetic operations listed in Table 20 are in order of precedence, which determines the order of evaluation in an equation without parentheses. The relational operators in the equations are:

=L=	Less than: left hand side (lhs) must be less than or equal to right hand side (rhs)
=G=	Greater than: lhs must be greater than or equal to rhs
=E=	Equality: lhs must equal to rhs
=N=	No relationships enforced between lhs and rhs. This type is rarely used.

Additionally, GAMS provides the numerical relationships and logical operators used to generate logical conditions for evaluating values of True or False. A result of zero is treated as a logical value of False, while a non-zero result is treated as a logical value of True. A complete numerical relationship operators and logical operators are listed in the Table 21 and Table 22, respectively.

Table 20 A List of Standard Arithmetic Operators

Operator	Description
**	Exponentiation
*, /	Multiplication and division
+, -	Addition and subtraction (unary and binary)

Table 21 A List of Numerical Relationship Operators

Operator	Description
lt, <	Strictly less than
le, <=	Less than or equal to
eq, =	Equal to
ne, <>	Not equal to
ge, >=	Greater than or equal to
gt, >	Strictly greater than

Table 22 A List of Logical Operators

Operator	Description
not	Not
And	And
Or	Inclusive or
Xor	Exclusive or

Table 23 The Truth Table Generated by the Logical Operators

Operands		Results			
A	b	a and b	a or b	a xor b	not a
0	0	0	0	0	1
0	non-zero	0	1	1	1
Non-zero	0	0	1	1	0
Non-zero	non-zero	1	1	0	0

Table 24 The Operator Precedence Order in case of Mixed Logical Conditions

Operation	Operator
Exponentiation	**
Numerical Operators	
Multiplication, Division	*, /
Unary operators - Plus, Minus	+, -
Binary operators - Addition, Subtraction	+, -
Numerical Relationship Operators	<, <=, =, <>, >=, >
Logical Operators	
Not	not
And	and
Or, xor	or, xor

The functions of the logical operators are expressed in Table 23. For the mixed logical conditions, the default operator precedence order used by GAMS in the absence of parenthesis is shown in Table 24 in decreasing order. For the formulation of equations, variables can appear on the left or right-hand side of an equation or on both sides. The system can automatically convert the equation to its standard form (variables on the left, no duplicate appearances) before calling the GAMS solver. For the convenience of input, the system also provides several special notations, such as summation (sum) and product (prod), minimum value (smin), maximum value (smax).

E-3. Functions Predefined in the System

There are two types of functions based on the type of argument: exogenous or endogenous. For exogenous arguments, the arguments are known, and examples are parameters and variable attributes. The expression is evaluated once when the model is set up. All functions except the random distribution functions, uniform and normal, are allowed. With endogenous arguments, the arguments are variables, and are, therefore, unknown. The function will be evaluated many times at intermediate points while the model is being solved. The occurrence of any function with endogenous arguments implies that the model is not linear and the use of the functions of "uniform" and "normal" are forbidden in an equation definition. Some built-in functions are listed in Table 25.

E-4. Scaling Option for Variables and Equations

To facilitate the translation between a natural model (no scaling) to a well scaled model, GAMS introduces the concept of a scale factor for variables and equations with a scaling option.

This feature is incorporated in the interactive on-line optimization system to provide a well-scaled optimization problem for GAMS to solve. To use the scaling option in the interactive on-line optimization, the user must highlight the scaling option in the variable declaration and the equations declaration windows. Then, the user must enter the values of the scale factors for the variables and equations that need to be scaled. The following describes how the scale factor is incorporated in the GAMS program and how to determine the value of a scale factor.

The scale factor on a variable V^s is used to relate the variable as seen by user (in natural model) V^u to the variable as seen by the optimization algorithm (in well scaled model) V^a as follows:

$$V^u = V^a \ \ V^s$$

This means that the scaled variable V^a will become around 1 if the scale factor V^s is chosen to represent the order of magnitude of the user variable V^u.

If the approximate expected value for a variable in the model is known, then the magnitude of this variable value is used as the scale factor of the variable. The scale factor can be specified by users through the Measured or Unmeasured Variables window. If the approximate expected values for some of the variables in the model are not available, these values can be found in the column list of the corresponding GAMS output file. The scale factor will not change the values of variables in the solution seen by users. GAMS uses the scale factor to scale variables and transfer the model into a well scaled model for optimization algorithm. When the optimal solution is found, GAMS will rescale the variables and transfer them back to user’s notation. The effect of scaling can only be viewed in the Column and Equation lists of the GAMS output files.

The scale factor for an equation is dependent on the order of magnitude of the equation coefficients. It is slightly different from the determination of scale factor for a variable that is dependent on the magnitude of the variable. An equation usually contains several terms, and it has several coefficients that may not be in the same order.

If the equation is linear, the coefficients of this equation is known. If the equation is nonlinear, then the equation is linearized first using the initial values. However, the linearized coefficients must be obtained from the equation list. Users can obtain the values of the linearized equation coefficients for nonlinear constraints from the equation list of the corresponding GAMS output file. To appropriately assign the scale factor for an equation, users need to carefully select the value of the scale factor based on the coefficients shown in equation list of the GAMS output file so that all coefficients will be in the range of 0.01 to 100 after scaling.

The column (variables) and equation lists are very important for nonlinear problems when scaling the variables and equations. It provides initial values of all variables and linearized constraint coefficients, which can be used to determine the scale factors for both variables and equations. It is suggested that the user turn off the scaling option for both variables and equations before GAMS is initiated.

Table 25 A List of Functions Predefined in the On-line Optimization System

Function	Description	Classification	Exogenous Classification	Endogenous model type
Abs	Absolute value	Non-smooth	Legal	DNLP
Arctan	Arctangent	Smooth	Legal	NLP
Ceil	Ceiling	Smooth	Legal	Illegal
Cos	Cosine	Discontinuous	Legal	NLP
Errorf	Error function	Smooth	Legal	NLP
Exp	Exponential	Smooth	Legal	NLP
Floor	Floor	Discontinuous	Legal	Illegal
Log	Natural log	Smooth	Legal	NLP
Log10	Common log	Smooth	Legal	NLP
Mapval	Mapping function	Discontinuous	Legal	Illegal
Max	Largest value	Non-smooth	Legal	DNLP
Min	Smallest value	Non-smooth	Legal	DNLP
Mod	Remainder	Discontinuous	Legal	Illegal
Normal	Normal random	Illegal	Illegal	Illegal
Power	Integer power	Smooth	Legal	NLP
Round	Rounding	Discontinuous	Legal	Illegal
Sign	Sign	Discontinuous	Legal	Illegal
Sin	Sine	Smooth	Legal	NLP
Sqr	Square	Smooth	Legal	NLP
Sqrt	Square root	Smooth	Legal	NLP
Trunc	Truncation	Discontinuous	Legal	Illegal
Uniform	Uniform random	Illegal	Illegal	Illegal

After the program ends, if the solution is correct and there was no difficulty in searching for an optimal solution, then the scaling option is not necessary. If the solution is not correct or some difficulty was encountered while searching for an optimal solution, then the scaling option must be incorporated in the program. In this case, users may instruct the system to include the column and equation lists in the output file. To do this, the user must change the default setting for the output files in window 12, the Output File Format Specification window. This will run the optimization program without the scaling option. Based on the values of variables in column list without scaling, users can decide the values of scale factors for variables, enter them in the

Measured Variables and Unmeasured variables windows, and highlight the icon “Include Scaling Option for variables” to scale the variables first. After the system executes the program, a new equation list, which incorporates the scale information of variables, is generated and can be used for equation scaling. Based on the linearized coefficients in this new equation list, users can determine the scale factors for the equations and enter them in the Equality Constraints and Inequality Constraints windows. Also, users must highlight the icon “Include Scaling Option for Equations” to add the Scaling Option in the programs.

E-5. Error Reporting

During compiling, executing, and solving the optimization problem, GAMS checks the input source code for program syntax, rearranges the information in the source code, and solves the optimization problem. At every step, GAMS records any error encountered and reports it in the GAMS output file. The following describes error reporting during solving the optimization problems.

Compilation Errors

The first type of error is a compilation error. When the GAMS compiler encounters an error in the input file, it inserts a coded error message inside the echo print on the line immediately following the scene of the offense. The message includes a $-symbol and an error number printed below the offending symbol (usually to the right). This error number is printed on a separate line starting with four asterisks (****). If more than one error occurs on a line, the $-signs may be suppressed and the error number is squeezed. GAMS programs are generated by the system, and no serious compilation errors are expected to appear. The most common error will be a spelling error, i.e., the variables defined in the equations may be mistyped and mismatch while declaring the variables. This will result in “variable undefined error”. GAMS will not list more than 10 errors on any single line. At the end of the echo print, a list of all error numbers encountered, together with a description of the probable cause of each error, will be printed. The error messages are self-explanatory and will not be listed here. Checking the first error is recommended because it has the highest priority.

Execution Errors

The second type of error is an execution error. Execution errors are usually caused by illegal arithmetic operations such as division by zero or taking the log of a negative number. GAMS prints a message on the output file with the line number of the offending statement and continues execution. A GAMS program should never abort with an unintelligible message from the computer’s operating system if an invalid operation is attempted. GAMS has rigorously defined an extended algebra that contains all operations including illegal ones. The model library problem [CRAZY] contains all non-standard operations and should be executed to study its exceptions. GAMS arithmetic is defined over the closed interval [-INF, INF] and contains values EPS (small but not zero), NA (not available), and UNDF (the result of an illegal operation). The results of illegal operations are propagated through the entire system and can be displayed with standard display statements. The model cannot be solved if errors have been detected previously.

Solve Errors

The last type of error is a solve error. The execution of a solve statement can trigger additional errors called MATRIX errors, which report on problems encountered during transformation of the model into a format required by the solver. Problems are most often caused by illegal or inconsistent bounds, or an extended range value being used as a matrix coefficient. Some solve statement require the evaluation of nonlinear functions and the computation of derivatives. Since these calculations are not carried out by the system but by other subsystems not under its direct control, errors associated with these calculations are reported in the solution report.

If the solver returns an intermediate solution because of evaluation errors, then a solution will still be attempted. The only fatal error in the system that can be caused by a solver program is the failure to return any solution at all. If this happens as mentioned above, all possible information is listed on the GAMS output file, but the solution will not be given.

XII. Acknowledgments

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APPENDIX A

CONSTRAINT EQUATIONS FOR SULFURIC ACID PROCESS

In this section, the constraint equations are listed for each of the units in the contact sulfuric acid process shown in Figure 9. The material and energy balances as well as reaction rate equation for the units in the reactor system are shown in Tables 26 through 31. The material and energy balances as well as heat transfer equations for the units in the heat exchanger network are shown in Table 31 through 37. The material and energy balance equations for absorption towers are shown in Table 38. Tables 39 through 41 give the material and energy balances for the various splitters and mixers in the process.

Table 26 The Process Constraint Equations for Sulfur Burner

Mole Balances	
Overall	$F_{06} - F_{07} - 0.01F_{50} = 0$ where $F_{06} = F_{06}^{O2} + F_{06}^{N2}$ $F_{07} = F_{07}^{O2} + F_{07}^{N2} + F_{07}^{SO2} + F_{07}^{SO3}$
Species	$O_2: \quad F_{06}^{(O_2)} - F_{07}^{(O_2)} - 1.01F_{50} = 0$ $N_2: \quad F_{06}^{(N_2)} - F_{07}^{(N_2)} = 0$ $SO_2: \quad F_{06}^{(SO_2)} - F_{07}^{(SO_2)} + 0.98F_{50} = 0$ $SO_3: \quad F_{06}^{(SO_3)} - F_{07}^{(SO_3)} + 0.02F_{50} = 0$ $S: \quad F_{50} - F_{07}^{(S)} - F_{07}^{(SO2)} - F_{07}^{(SO3)} = 0$ where $F_{06}^{(SO_2)} = 0,\ F_{06}^{(SO_3)} = 0,\ F_{07}^{(S)} = 0$
Energy Balances	
Overall	$F_{50}h^{(sulfur)} + \sum_i F_{06}^{(i)}h_{06}^{(i)} + F_{50}\Delta h_{rxn}^{SO_2} + 0.02F_{50}\Delta h_{rxn}^{SO_3} - \sum_i F_{07}^{(i)}h_{07}^{(i)} - Q_{loss} = 0$ where $\Delta h_{rxn}^{SO_2} = h(T)^{S} + h(T)^{O_2} - h(T)^{SO_2}$, $\Delta h_{rxn}^{SO_3} = 1.827\times(-24,097 - 0.26T + 1.69\times10^{-3}T^2 + 1.5\times10^5/T),\ BTU/lb-mol$
Enthalpy Function	$h^i_k(T) = R(a_1^iT + \frac{1}{2}a_2^iT^2 + \frac{1}{3}a_3^iT^3 + \frac{1}{4}a_4^iT^4 + \frac{1}{5}a_5^iT^5 + b_1^i - H_{298}^i) \quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2, sulfur(L);\ k = 06, 07$

Table 27 The Process Constraint Equations for Converter I

Material Balances	
Overall	$\frac{dF_I}{dL} = -\frac{1}{2} r_{SO_3} A$ $F_I = F10,\ at\ L = 0;\quad F_I = F11,\ at\ L = l_I$ $where\ r_{SO_3} = r^I_{SO_2} E^I_f \rho^I_B;\ F_I = \sum_i F_I^{(i)}$ $F_I = F_I^{SO2} + F_I^{SO3} + F_I^{O2} + F_I^{N2}$
Species	$SO_3:\ \frac{dF_I^{(SO_3)}}{dL} = r_{SO_3} A$ $SO_2:\ \frac{dF_I^{(SO_2)}}{dL} = -r_{SO_3} A$ $O_2:\ \frac{dF_I^{(O_2)}}{dL} = -\frac{1}{2} r_{SO_3} A$ $N_2:\quad F_{11}^{(N_2)} - F_{10}^{(N_2)} = 0$ $B.\ C.:\ F_I^{(i)} = F10^{(i)},\ at\ L = 0;$ $F_I^{(i)} = F11^{(i)},\ at\ L = l_I$ $where\ \ i = SO_3, SO_2, O_2$
Energy Balances	
Overall	$\frac{dH_I}{dL} = r_{SO_3} \Delta h_{rxn}^{SO_3} A$ $H_I = H10,\ at\ L = 0;\ H_I = H11,\ at\ L = l_I$ $where\ H_I = \sum_i F_I^{(i)} h_I^{(i)}$
Enthalpy Function	$h^i_I(T) = R(a_1^i T + \frac{1}{2} a_2^i T^2 + \frac{1}{3} a_3^i T^3 + \frac{1}{4} a_4^i T^4 + \frac{1}{5} a_5^i T^5 + b_1^i - H^i_{298})\quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2$

Table 28 The Process Constraint Equations for Converter II

Material Balances	
Overall	$\frac{dF_{II}}{dL} = -\frac{1}{2} r_{SO_3} A$ $F_{II} = F12, \text{ at } L = 0; \quad F_{II} = F13, \text{ at } L = l_{II}$ $\text{where } r_{SO_3} = r^{II}_{SO_2} E_f^{II} \rho_B^{II}; \; F_{II} = \sum_i F_{II}^{(i)}$ $F_{II} = F_{II}^{SO2} + F_{II}^{SO3} + F_{II}^{O2} + F_{II}^{N2}$
Species	$SO_3\text{:} \; \frac{dF_{II}^{(SO_3)}}{dL} = r_{SO_3} A$ $SO_2\text{:} \; \frac{dF_{II}^{(SO_2)}}{dL} = -r_{SO_3} A$ $O_2\text{:} \; \frac{dF_{II}^{(O_2)}}{dL} = -\frac{1}{2} r_{SO_3} A$ $N_2\text{:} \quad F_{13}^{(N_2)} - F_{12}^{(N_2)} = 0$ $B.\ C.\text{:} \; F_{II}^{(i)} = F12^{(i)}, \text{ at } L = 0;$ $F_{II}^{(i)} = F13^{(i)}, \text{ at } L = l_{II}$ $\text{where } \; i = SO_3, SO_2, O_2$
Energy Balances	
Overall	$\frac{dH_{II}}{dL} = r_{SO_3} \Delta h_{rxn}^{SO_3} A$ $H_{II} = H12, \text{ at } L = 0; \; H_{II} = H13, \text{ at } L = l_{II}$ $\text{where } H_{II} = \sum_i F_{II}^{(i)} h_{II}^{(i)}$
Enthalpy Function	$h^i_{II}(T) = R(a_1^i T + \frac{1}{2} a_2^i T^2 + \frac{1}{3} a_3^i T^3 + \frac{1}{4} a_4^i T^4 + \frac{1}{5} a_5^i T^5 + b_1^i - H_{298}^i) \quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2$

Table 29 The Process Constraint Equations for Converter III

Material Balances	
Overall	$\frac{dF_{III}}{dL} = -\frac{1}{2} r_{SO_3} A$ $F_{III} = F20,\ at\ L = 0;\quad F_{III} = F21,\ at\ L = l_{III}$ $where\ r_{SO_3} = r^{III}_{SO_2} E_f^{III} \rho_B^{III};\ F_{III} = \sum_i F_{III}^{(i)}$ $F_{III} = F_{III}^{SO2} + F_{III}^{SO3} + F_{III}^{O2} + F_{III}^{N2}$
Species	$SO_3:\ \frac{dF_{III}^{(SO_3)}}{dL} = r_{SO_3} A$ $SO_2:\ \frac{dF_{III}^{(SO_2)}}{dL} = -r_{SO_3} A$ $O_2:\ \frac{dF_{III}^{(O_2)}}{dL} = -\frac{1}{2} r_{SO_3} A$ $N_2:\quad F_{21}^{(N_2)} - F_{20}^{(N_2)} = 0$ $B.\ C.:\ F_{III}^{(i)} = F20^{(i)},\ at\ L = 0;$ $F_{III}^{(i)} = F21^{(i)},\ at\ L = l_{III}$ $where\ \ i = SO_3, SO_2, O_2$
Energy Balances	
Overall	$\frac{dH_{III}}{dL} = r_{SO_3} \Delta h_{rxn}^{SO_3} A$ $H_{III} = H20,\ at\ L = 0;\ H_{III} = H21,\ at\ L = l_{III}$ $where\ H_{III} = \sum_i F_{III}^{(i)} h_{III}^{(i)}$
Enthalpy Function	$h^i_{III}(T) = R(a_1^i T + \frac{1}{2} a_2^i T^2 + \frac{1}{3} a_3^i T^3 + \frac{1}{4} a_4^i T^4 + \frac{1}{5} a_5^i T^5 + b_1^i - H_{298}^i)\quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2$

Table 30 The Process Constraint Equations for Converter IV

Material Balances	
Overall	$\frac{dF_{IV}}{dL} = -\frac{1}{2} r_{SO_3} A$ $F_{IV} = F22,\ at\ L = 0;\quad F_{IV} = F23,\ at\ L = l_{IV}$ $where\ r_{SO_3} = r^{IV}_{SO_2} E_f^{IV} \rho_B^{IV};\ F_{IV} = \sum_i F_{IV}^{(i)}$ $F_{IV} = F_{IV}^{SO2} + F_{IV}^{SO3} + F_{IV}^{O2} + F_{IV}^{N2}$
Species	$SO_3:\ \frac{dF_{IV}^{(SO_3)}}{dL} = r_{SO_3} A$ $SO_2:\ \frac{dF_{IV}^{(SO_2)}}{dL} = -r_{SO_3} A$ $O_2:\ \frac{dF_{IV}^{(O_2)}}{dL} = -\frac{1}{2} r_{SO_3} A$ $N_2:\quad F_{23}^{(N_2)} - F_{22}^{(N_2)} = 0$ $B.\ C.:\ F_{IV}^{(i)} = F22^{(i)},\ at\ L = 0;$ $F_{IV}^{(i)} = F23^{(i)},\ at\ L = l_{IV}$ $where\ \ i = SO_3, SO_2, O_2$
Energy Balances	
Overall	$\frac{dH_{IV}}{dL} = r_{SO_3} \Delta h_{rxn}^{SO_3} A$ $H_{IV} = H22,\ at\ L = 0;\ H_{IV} = H23,\ at\ L = l_{IV}$ $where\ H_{IV} = \sum_i F_{IV}^{(i)} h_{IV}^{(i)}$
Enthalpy Function	$h^{i}_{IV}(T) = R(a_1^{i} T + \frac{1}{2} a_2^{i} T^2 + \frac{1}{3} a_3^{i} T^3 + \frac{1}{4} a_4^{i} T^4 + \frac{1}{5} a_5^{i} T^5 + b_1^{i} - H_{298}^{i})\quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2$

Table 31 The Constraint Equations for Hot Inter-Pass Heat Exchanger

Material Balances	
Overall	$(F_{14}^{(SO_3)}+F_{14}^{(SO_2)}+F_{14}^{(O_2)}+F_{14}^{(N_2)})-(F_{13}^{(SO_3)}+F_{13}^{(SO_2)}+F_{13}^{(O_2)}+F_{13}^{(N_2)})=0$ $(F_{20}^{(SO_3)}+F_{20}^{(SO_2)}+F_{20}^{(O_2)}+F_{20}^{(N_2)})-(F_{19}^{(SO_3)}+F_{19}^{(SO_2)}+F_{19}^{(O_2)}+F_{19}^{(N_2)})=0$
Species	$O_2: \quad F_{14}^{(O_2)}-F_{13}^{(O_2)}=0, \qquad F_{20}^{(O_2)}-F_{19}^{(O_2)}=0$ $N_2: \quad F_{14}^{(N_2)}-F_{13}^{(N_2)}=0, \qquad F_{20}^{(N_2)}-F_{19}^{(N_2)}=0$ $SO_2: \quad F_{14}^{(SO_2)}-F_{13}^{(SO_2)}=0, \qquad F_{20}^{(SO_2)}-F_{19}^{(SO_2)}=0$ $SO_3: \quad F_{14}^{(SO_3)}-F_{13}^{(SO_3)}=0, \qquad F_{20}^{(SO_3)}-F_{19}^{(SO_3)}=0$
Energy Balances	
Overall	$\left(\sum_i F_{14}^{(i)}h_{14}^{(i)}-\sum_i F_{13}^{(i)}h_{13}^{(i)}\right)-\left(\sum_i F_{19}^{(i)}h_{19}^{(i)}-\sum_i F_{20}^{(i)}h_{20}^{(i)}\right)+H_{loss}=0$ where $h^i_k(T) = R(a_1^iT+\frac{1}{2}a_2^iT^2+\frac{1}{3}a_3^iT^3+\frac{1}{4}a_4^iT^4+\frac{1}{5}a_5^iT^5+b_1^i-H_{298}^i)$ $i = SO_2, SO_3, O_2, N_2; \; k = 13, 14, 19, 20$
Heat Transfer	$\left(\sum_i F_{20}^{(i)}h_{20}^{(i)}-\sum_i F_{19}^{(i)}h_{19}^{(i)}\right)-(U_{ex66}A_{ex66}\Delta T_{lm})=0$

Table 32 The Constraint Equations for Cold Inter-Pass Heat Exchanger

Material Balances	
Overall	$(F_{15}^{(SO_3)}+F_{15}^{(SO_2)}+F_{15}^{(O_2)}+F_{15}^{(N_2)})-(F_{14}^{(SO_3)}+F_{14}^{(SO_2)}+F_{14}^{(O_2)}+F_{14}^{(N_2)})=0$ $(F_{19}^{(SO_3)}+F_{19}^{(SO_2)}+F_{19}^{(O_2)}+F_{19}^{(N_2)})-(F_{16}^{(SO_3)}+F_{16}^{(SO_2)}+F_{16}^{(O_2)}+F_{16}^{(N_2)})=0$
Species	$O_2: \quad F_{15}^{(O_2)}-F_{14}^{(O_2)}=0, \qquad F_{19}^{(O_2)}-F_{16}^{(O_2)}=0$ $N_2: \quad F_{15}^{(N_2)}-F_{14}^{(N_2)}=0, \qquad F_{19}^{(N_2)}-F_{16}^{(N_2)}=0$ $SO_2: \quad F_{15}^{(SO_2)}-F_{14}^{(SO_2)}=0, \qquad F_{19}^{(SO_2)}-F_{16}^{(SO_2)}=0$ $SO_3: \quad F_{15}^{(SO_3)}-F_{14}^{(SO_3)}=0, \qquad F_{19}^{(SO_3)}-F_{16}^{(SO_3)}=0$
Energy Balances	
Overall	$\left(\sum_i F_{15}^{(i)}h_{15}^{(i)}-\sum_i F_{14}^{(i)}h_{14}^{(i)}\right)-\left(\sum_i F_{16}^{(i)}h_{16}^{(i)}-\sum_i F_{19}^{(i)}h_{19}^{(i)}\right)+H_{loss}=0$ where $h^{i}_{k}(T) = R(a_1^iT+\frac{1}{2}a_2^iT^2+\frac{1}{3}a_3^iT^3+\frac{1}{4}a_4^iT^4+\frac{1}{5}a_5^iT^5+b_1^i-H_{298}^i)$ $i = SO_2, SO_3, O_2, N_2; \; k = 14, 15, 16, 19$
Heat Transfer	$\left(\sum_i F_{19}^{(i)}h_{19}^{(i)}-\sum_i F_{16}^{(i)}h_{16}^{(i)}\right)-\left(U_{ex65}A_{ex65}\Delta T_{lm}\right)=0$

Table 33 The Constraint Equations for the Superheater1

Material Balances	
Overall	$(F_{21}^{(SO_3)}+F_{21}^{(SO_2)}+F_{21}^{(O_2)}+F_{21}^{(N_2)})-(F_{22}^{(SO_3)}+F_{22}^{(SO_2)}+F_{22}^{(O_2)}+F_{22}^{(N_2)})=0$ $F_{shp1}-F_{ss4}=0$
Species	$O_2: \quad F_{21}^{(O_2)}-F_{22}^{(O_2)}=0$ $N_2: \quad F_{21}^{(N_2)}-F_{22}^{(N_2)}=0$ $SO_2: \quad F_{21}^{(SO_2)}-F_{22}^{(SO_2)}=0$ $SO_3: \quad F_{21}^{(SO_3)}-F_{22}^{(SO_3)}=0$
Energy Balances	
Overall	$\left(\sum_i F_{22}^{(i)}h_{22}^{(i)}-\sum_i F_{21}^{(i)}h_{21}^{(i)}\right)-(F_{ss4}h_{sss4}-F_{shp1}h_{shp1})+H_{loss}=0$ where $h^{i}_{k}(T)=R(a_1T+\frac{1}{2}a_2T^2+\frac{1}{3}a_3T^3+\frac{1}{4}a_4T^4+\frac{1}{5}a_5T^5+b_1-H_{298})$ MJ/kmol $i=SO_2,SO_3,O_2,N_2;\ k=21,22$ $h_{ss4}=h_{ss2}$ $h_{shp1}=5.32661T-0.2839015P-7.352389\times10^{-3}T^2+3.581547\times10^{-6}T^3-7.289244\times10^{-5}P^2+4.595405\times10^{-4}TP$ BTU/lb,
Heat Transfer	$\left(\sum_i F_{21}^{(i)}h_{21}^{(i)}-\sum_i F_{22}^{(i)}h_{22}^{(i)}\right)-H_{loss}-(U_{sh1}A_{sh1})T_{lm}=0$

Table 34 The Constraint Equations for the Superheater2

Material Balances	
Overall	$(F_{23}^{(SO_3)}+F_{23}^{(SO_2)}+F_{23}^{(O_2)}+F_{23}^{(N_2)})-(F_{235}^{(SO_3)}+F_{235}^{(SO_2)}+F_{235}^{(O_2)}+F_{235}^{(N_2)})=0$ $F_{shp2}-F_{ss5}=0$
Species	$O_2:\quad F_{23}^{(O_2)}-F_{235}^{(O_2)}=0$ $N_2:\quad F_{23}^{(N_2)}-F_{235}^{(N_2)}=0$ $SO_2:\quad F_{23}^{(SO_2)}-F_{235}^{(SO_2)}=0$ $SO_3:\quad F_{23}^{(SO_3)}-F_{235}^{(SO_3)}=0$
Energy Balances	
Overall	$\left(\sum_i F_{235}^{(i)}h_{235}^{(i)}-\sum_i F_{23}^{(i)}h_{23}^{(i)}\right)-(F_{ss5}h_{ss5}-F_{shp2}h_{shp2})+H_{loss}=0$ where $h^i_k(T)=R(a_1T+\frac{1}{2}a_2T^2+\frac{1}{3}a_3T^3+\frac{1}{4}a_4T^4+\frac{1}{5}a_5T^5+b_1-H_{298})$ MJ/kmol $i=SO_2,SO_3,O_2,N_2;\ k=23,235$ $h_{ss5}=h_{ss2}$ $h_{shp2}=5.32661T-0.2839015P-7.352389\times10^{-3}T^2+3.581547\times10^{-6}T^3-7.289244\times10^{-5}P^2+4.595405\times10^{-4}TP$ BTU/lb,
Heat Transfer	$\left(\sum_i F_{23}^{(i)}h_{23}^{(i)}-\sum_i F_{235}^{(i)}h_{235}^{(i)}\right)-H_{loss}-(U_{sh2}A_{sh2})T_{lm})=0$

Table 35 The Constraint Equations for the Waste Heat Boiler

Material Balances	
Overall	$(F_{09}^{(SO_3)}+F_{09}^{(SO_2)}+F_{09}^{(O_2)}+F_{09}^{(N_2)})-(F_{08}^{(SO_3)}+F_{08}^{(SO_2)}+F_{08}^{(O_2)}+F_{08}^{(N_2)})=0$ $F_{sw1a}-F_{ss1a}=0$
Species	$O_2: \quad F_{08}^{(O_2)}-F_{09}^{(O_2)}=0$ $N_2: \quad F_{08}^{(N_2)}-F_{09}^{(N_2)}=0$ $SO_2: \quad F_{08}^{(SO_2)}-F_{09}^{(SO_2)}=0$ $SO_3: \quad F_{08}^{(SO_3)}-F_{09}^{(SO_3)}=0$
Energy Balances	
Overall	$\left(\sum_i F_{09}^{(i)}h_{09}^{(i)}-\sum_i F_{08}^{(i)}h_{08}^{(i)}\right)-(F_{sw1a}h_{sw1a}-F_{ss1a}h_{ss1a})+H_{loss}=0$ where $h^i{}_k(T)=R(a_1T+\frac{1}{2}a_2T^2+\frac{1}{3}a_3T^3+\frac{1}{4}a_4T^4+\frac{1}{5}a_5T^5+b_1-\Delta H_{298})$ $MJ/kmol$ $i=SO_2,SO_3,O_2,N_2;\ k=08,09$ $h_{sw1a}=h_{sw1}$ $h_{ss1a}=bdfrac((1.0861707T-5.63134\times10^{-4}T^2+8.34491\times10^{-7}T^3-\frac{1.14266\times10^4}{T}+\frac{1.01824\times10^6}{T^2})+(1-bdfrac)((5.32661T-0.2839015P-7.352389\times10^{-3}T^2+3.581547\times10^{-6}T^3-7.289244\times10^{-5}P^2+4.595405\times10^{-4}TP)$ BTU/lb, bdfrac, boiler blowdown fraction = 0.1
Heat Transfer	$\left(\sum_i F_{08}^{(i)}h_{08}^{(i)}-\sum_i F_{09}^{(i)}h_{09}^{(i)}\right)-H_{loss}-(U_{wboiler}A_{wboiler})\Delta T_{lm})=0$

Table 36 The Constraint Equations for the Converter Boiler

Material Balances	
Overall	$(F_{12}^{(SO_3)} \% F_{12}^{(SO_2)} \% F_{12}^{(O_2)} \% F_{12}^{(N_2)}) \&$ $(F_{11}^{(SO_3)} \% F_{11}^{(SO_2)} \% F_{11}^{(O_2)} \% F_{11}^{(N_2)}) \ ' \ 0$ $F_{sw1b} \& F_{ss1b} \ ' \ 0$
Species	$O_2: \quad F_{11}^{(O_2)} \& F_{12}^{(O_2)} \ ' \ 0$ $N_2: \quad F_{11}^{(N_2)} \& F_{12}^{(N_2)} \ ' \ 0$ $SO_2: \quad F_{11}^{(SO_2)} \& F_{12}^{(SO_2)} \ ' \ 0$ $SO_3: \quad F_{11}^{(SO_3)} \& F_{12}^{(SO_3)} \ ' \ 0$
Energy Balances	
Overall	$\left(\mathbf{j}_i \ F_{12}^{(i)} h_{12}^{(i)} \& \ \mathbf{j}_i \ F_{11}^{(i)} h_{11}^{(i)} \right) \& (F_{Sw1b} h_{sw1b} \& F_{ss1b} h_{ss1b}) \% H_{loss} \ ' \ 0$ where $h^i{}_k(T) \ ' \ R(a_1 T \% \frac{1}{2} a_2 T^2 \% \frac{1}{3} a_3 T^3$ $\% \frac{1}{4} a_4 T^4 \% \frac{1}{5} a_5 T^5 \% b_1 \& H_{298}) \quad MJ/kmol$ $i \ ' \ SO_2, SO_3, O_2, N_2; \ k \ ' \ 11, 12$ $h_{sw1b} = h_{sw1}$ $h_{ss1b} \ ' \ bdfrac((1.0861707T \& 5.63134 \times 10^{\&4} T^2$ $\% 8.34491 \times 10^{\&7} T^3 \& \frac{1.14266 \times 10^4}{T}$ $\% \frac{1.01824 \times 10^6}{T^2}) \% (1 \& bdfrac)((5.32661T \& 0.2839015P$ $\& 7.352389 \times 10^{\&3} T^2 \% 3.581547 \times 10^{\&6} T^3$ $\& 7.289244 \times 10^{\&5} P^2 \% 4.595405 \times 10^{\&4} TP)$ $BTU/lb,$ bdfrac, boiler blowdown fraction = 0.1
Heat Transfer	$\left(\mathbf{j}_i \ F_{11}^{(i)} h_{11}^{(i)} \& \ \mathbf{j}_i \ F_{12}^{(i)} h_{12}^{(i)} \right) \& H_{loss} \& (U_{cboiler} A_{cboiler}) \ T_{lm}) \ ' \ 0$

Table 37 The Constraint Equations for the Economizer

Material Balances	
Overall	$(F_{235}^{(SO_3)}+F_{235}^{(SO_2)}+F_{235}^{(O_2)}+F_{235}^{(N_2)})-(F_{24}^{(SO_3)}+F_{24}^{(SO_2)}+F_{24}^{(O_2)}+F_{24}^{(N_2)})=0$ $F_{sbfw}-F_{sw1}=0$
Species	$O_2: \quad F_{235}^{(O_2)}-F_{24}^{(O_2)}=0$ $N_2: \quad F_{235}^{(N_2)}-F_{24}^{(N_2)}=0$ $SO_2: \quad F_{235}^{(SO_2)}-F_{24}^{(SO_2)}=0$ $SO_3: \quad F_{235}^{(SO_3)}-F_{24}^{(SO_3)}=0$
Energy Balances	
Overall	$\left(\sum_i F_{24}^{(i)}h_{24}^{(i)}-\sum_i F_{235}^{(i)}h_{235}^{(i)}\right)-(F_{sbfw}h_{sbfw}-F_{sw1}h_{sw1})+H_{loss}=0$ where $h^i_k(T)=R(a_1T+\frac{1}{2}a_2T^2+\frac{1}{3}a_3T^3+\frac{1}{4}a_4T^4+\frac{1}{5}a_5T^5+b_1-H_{298})$ MJ/kmol $i=SO_2,SO_3,O_2,N_2;\ k=235,24$ $h_n=1.0861707T-5.63134\times10^{-4}T^2+8.34491\times10^{-7}T^3-\frac{1.14266\times10^4}{T}+\frac{1.01824\times10^6}{T^2},\quad BTU/lb$ $n=sbfw,sw1$
Heat Transfer	$\left(\sum_i F_{235}^{(i)}h_{235}^{(i)}-\sum_i F_{24}^{(i)}h_{24}^{(i)}\right)-H_{loss}-(U_{econ}A_{econ})\,T_{lm})=0$

Table 38 The Process Constraint Equations for the Interpass Absorption Tower and Final Absorption Tower

Material Balances for Interpass Absorption Tower	
Overall	$F_{15} - F_{15}^{(SO_3)} = F_{16}$
Species	$O_2: \quad F_{16}^{(O_2)} - F_{15}^{(O_2)} = 0$ $N_2: \quad F_{16}^{(N_2)} - F_{15}^{(N_2)} = 0$ $SO_2: \quad F_{16}^{(SO_2)} - F_{15}^{(SO_2)} = 0$ $SO_3: \quad F_{16}^{(SO_3)} = 0$
Material Balances for Final Absorption Tower	
Overall	$F_{24} - F_{24}^{(SO_3)} = F_{25}$
Species	$O_2: \quad F_{25}^{(O_2)} - F_{24}^{(O_2)} = 0$ $N_2: \quad F_{25}^{(N_2)} - F_{24}^{(N_2)} = 0$ $SO_2: \quad F_{25}^{(SO_2)} - F_{24}^{(SO_2)} = 0$ $SO_3: \quad F_{25}^{(SO_3)} = 0$

Table 39 The Process Constraint Equations for the Splitter after the Sulfur Burner

Material Balances	
Overall	$(F_{07}^{(SO_3)}+F_{07}^{(SO_2)}+F_{07}^{(O_2)}+F_{07}^{(N_2)}) = (F_{08}^{(SO_3)}+F_{08}^{(SO_2)}+F_{08}^{(O_2)}+F_{08}^{(N_2)}) + (F_{08a}^{(SO_3)}+F_{08a}^{(SO_2)}+F_{08a}^{(O_2)}+F_{08a}^{(N_2)})$
Species	$O_2: \quad F_{07}^{(O_2)}-F_{08}^{(O_2)}-F_{08a}^{(O_2)} = 0$ $N_2: \quad F_{07}^{(N_2)}-F_{08}^{(N_2)}-F_{08a}^{(N_2)} = 0$ $SO_2: \quad F_{07}^{(SO_2)}-F_{08}^{(SO_2)}-F_{08a}^{(SO_2)} = 0$ $SO_3: \quad F_{07}^{(SO_3)}-F_{08}^{(SO_3)}-F_{08a}^{(SO_3)} = 0$
Energy Balances	
Overall	$\sum_i F_{07}^{(i)}h_{07}^{(i)} - \sum_i F_{08}^{(i)}h_{08}^{(i)} - \sum_i F_{08a}^{(i)}h_{08a}^{(i)} = 0$ where $h^i_k(T) = R(a_1T+\frac{1}{2}a_2T^2+\frac{1}{3}a_3T^3+\frac{1}{4}a_4T^4+\frac{1}{5}a_5T^5+b_1-H_{298})$ $MJ/kmol$ $i = SO_2, SO_3, O_2, N_2;\ k = 07, 08, 08a$

Table 40 The Process Constraint Equations for the Mixer after the Waste Boiler

Material Balances	
Overall	$(F_{10}^{(SO_3)}+F_{10}^{(SO_2)}+F_{10}^{(O_2)}+F_{10}^{(N_2)}) = (F_{08a}^{(SO_3)}+F_{08a}^{(SO_2)}+F_{08a}^{(O_2)}+F_{08a}^{(N_2)})+$ $(F_{09}^{(SO_3)}+F_{09}^{(SO_2)}+F_{09}^{(O_2)}+F_{09}^{(N_2)})$
Species	$O_2: \quad F_{10}^{(O_2)}-F_{08a}^{(O_2)}-F_{09}^{(O_2)} = 0$ $N_2: \quad F_{10}^{(N_2)}-F_{08a}^{(N_2)}-F_{09}^{(N_2)} = 0$ $SO_2: \quad F_{10}^{(SO_2)}-F_{08a}^{(SO_2)}-F_{09}^{(SO_2)} = 0$ $SO_3: \quad F_{10}^{(SO_3)}-F_{08a}^{(SO_3)}-F_{09}^{(SO_3)} = 0$
Energy Balances	
Overall	$\sum_i F_{10}^{(i)}h_{10}^{(i)} - \sum_i F_{09}^{(i)}h_{09}^{(i)} - \sum_i F_{08a}^{(i)}h_{08a}^{(i)} = 0$ where $h^i_k(T) = R(a_1T+\frac{1}{2}a_2T^2+\frac{1}{3}a_3T^3+\frac{1}{4}a_4T^4+\frac{1}{5}a_5T^5+b_1-H_{298}) \quad MJ/kmol$ $i = SO_2, SO_3, O_2, N_2; \; k = 08a, 09, 10$

Table 41 The Process Constraint Equations for the Steam Mixer

Material Balances	
Overall	$F_{ss1}^{(H_2O)} = F_{ss1a}^{(H_2O)} + F_{ss1b}^{(H_2O)}$
Energy Balances	
Overall	$F_{ss1}h_{ss1} - F_{ss1a}h_{ss1a} - F_{ss1b}h_{ss1b} = 0$ where $h_n = bdfrac((1.0861707T - 5.63134\times10^{-4}T^2 + 8.34491\times10^{-7}T^3 - \frac{1.14266\times10^4}{T} + \frac{1.01824\times10^6}{T^2}) + (1 - bdfrac)((5.32661T - 0.2839015P - 7.352389\times10^{-3}T^2 + 3.581547\times10^{-6}T^3 - 7.289244\times10^{-5}P^2 + 4.595405\times10^{-4}TP)$ $BTU/lb,$ $n = ss1, ss1a, ss1b$ bdfrac, boiler blowdown fraction = 0.1

APPENDIX B
Full Output File for Economic Optimization of Online Optimization for D-Train Sulfuric Acid Process

```
Economic Optimization Program                                   01/25/01 17:27:26  PAGE      1
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  2
  5
  6  SCALARS
  7  o2   / 32 /
  8  so2  / 64 /
  9  so3  / 80 /
 10  h2o  / 18 /
 11  h2so4  / 98 /
 12  n2  / 28 /
 13  ;
 14
 15  SCALARS
 16  h1  / 0.4725 /
 17  h2  / 0.5225 /
 18  h3  / 0.56 /
 19  h4  / 0.685 /
 20  av120  / 68.357 /
 21  av110  / 91.043 /
 22  phio  / 0.91 /
 23  Pr  / 0.83 /
 24  Area  / 1134 /
 25  BD120  / 38.1 /
 26  BD110  / 33.8 /
 27  factor1  / 0.002326 /
 28  factor2  / 0.04191 /
 29  bdfrac  / 0.1 /
 30  cp_water  / 0.04187 /
 31  factor3  / 4.187 /
 32  ;
 33  SCALARS
 34  cmv_so2  / 123.77 /
 35  cmv_so3  / 126.948 /
 36  cmv_o2  / 73.4 /
 37  cmv_n2  / 89.5 /
 38  ct_so2  / 430.36 /
 39  ct_so3  / 491.46 /
 40  ct_o2  / 154.6 /
 41  ct_n2  / 126.2 /
 42  Viscc_so2  / 0.099551 /
 43  Viscc_so3  / 0.116947 /
 44  Viscc_o2  / 0.059773 /
 45  Viscc_n2  / 0.04426 /
 46  ;
 47  SCALARS
 48  H298_so2  /-35701 /
 49     H298_so3  /-47598 /
 50
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 50  H298_o2  / 0 /
 51  H298_n2  / 0 /
 52  b1_so2  /-36908 /
 53  b1_so3  /-48932 /
 54  b1_o2  /-1063.9 /
 55  b1_n2  /-1047 /
 56  H298_s  / 0 /
 57  b1_s  / 8291.3 /
 58  b2_so2  /-37558 /
 59  b2_so3  /-50211 /
 60  b2_o2  /-1216 /
 61  b2_n2  /-923.95 /
 62  b2_s  /-590.87 /
 63  R  / 0.0083145 /
 64  ;
 65  SCALARS
 66  Ex65area  / 0.32 /
 67  Ex66area  / 0.32 /
 68  Ex67area  / 0.04284 /
 69  Ex68area  / 0.0338 /
 70  Ex71area  / 0.4005 /
 71  BLRarea  / 0.2571 /
 72  CLRarea  / 0.2 /
 73  ;
 74  SCALARS
 75  blrloss  / 0.9839 /
 76  clrloss  / 0.28496 /
```

```
ex65loss  / 0.2341 /
ex66loss  / 0.18096 /
ex67loss  / 0.06178 /
ex68loss  / 0.01406 /
ex71loss  / 0.20876 /
frnloss  / 5.24521 /
;
SCALARS
cstsulfur  / 1.7 /
cstfeedw  / 0.00675 /
cstdilutw  / 0.00198 /
cstacid  / 0.02134 /
csthpsteam  / 0.103 /
;

* The following are the Measured Variables
VARIABLES
F06, f50, fsbfw, O2percent, Pshp1, Pshp2, Pss2, SO2ppm,
T06, T07, T09, T10, T11, T12, T13, T15,

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T16, T19, T20, T21, T22, T23, T235, T24,
T25, Tsbfw, TSHP1, TSHP2, TSW1;

VARIABLE ObjVar objective or profit function;
* The following are the Unmeasured Variables
VARIABLES
ai1201, ai1202, ai1203, ai1204, ai1205, aii1201, aii1202, aii1203,
aii1204, aii1205, aiii1101, aiii1102, aiii1103, aiii1104, aiii1105, aiv1101,
aiv1102, aiv1103, aiv1104, aiv1105, blrdt, bypass, ci1201, ci1202,
ci1203, ci1204, ci1205, cii1201, cii1202, cii1203, cii1204, cii1205,
ciii1101, ciii1102, ciii1103, ciii1104, ciii1105, civ1101, civ1102, civ1103,
civ1104, civ1105, clrdt, Cpi1, Cpi2, Cpi3, Cpi4, Cpi5,
Cpii1, Cpii2, Cpii3, Cpii4, Cpii5, Cpiii1, Cpiii2, Cpiii3,
Cpiii4, Cpiii5, Cpiv1, Cpiv2, Cpiv3, Cpiv4, Cpiv5, di1201,
di1202, di1203, di1204, di1205, dii1201, dii1202, dii1203, dii1204,
dii1205, diii1101, diii1102, diii1103, diii1104, diii1105, div1101, div1102,
div1103, div1104, div1105, dti1, dti2, dti3, dti4, dti5,
dtii1, dtii2, dtii3, dtii4, dtii5, dtiii1, dtiii2, dtiii3,
dtiii4, dtiii5, dtiv1, dtiv2, dtiv3, dtiv4, dtiv5, emiss,
emiss1, enthi1, enthi2, enthi3, enthi4, enthi5, enthii1, enthii2,
enthii3, enthii4, enthii5, enthiii1, enthiii2, enthiii3, enthiii4, enthiii5,
enthiv1, enthiv2, enthiv3, enthiv4, enthiv5, ex65dT, ex66dt, ex67dt,
ex68dT, ex71dT, f06n2, f06o2, f07, f07n2, f07o2, f07so2,
f07so3, f08, f08a, f08an2, f08ao2, f08aso2, f08aso3, f08n2,
f08o2, f08so2, f08so3, f09, f09n2, f09o2, f09so2, f09so3,
f10, f10n2, f10o2, f10so2, f10so3, f11, f11n2, f11o2,
f11so2, f11so3, f12, f12n2, f12o2, f12so2, f12so3, f13,
f13n2, f13o2, f13so2, f13so3, f14, f14n2, f14o2, f14so2,
f14so3, f15, f15n2, f15o2, f15so2, f15so3, f16, f16n2,
f16o2, f16so2, f19, f19n2, f19o2, f19so2, f20, f20n2,
f20o2, f20so2, f21, f21n2, f21o2, f21so2, f21so3, f22,
f22n2, f22o2, f22so2, f22so3, f23, f235, f235n2, f235o2,
f235so2, f235so3, f23n2, f23o2, f23so2, f23so3, f24, f24n2,
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Visci1, Visci2, Visci3, Visci4, Visci5, Viscii1, Viscii2, Viscii3,
Viscii4, Viscii5, Visciii1, Visciii2, Visciii3, Visciii4, Visciii5, Visciv1,
Visciv2, Visciv3, Visciv4, Visciv5, wbratio, Xprod;

* The following are the Parameters in the Model
SCALARS
blrU       / 0.3598 /
clrU       / 0.2358 /
effi       / 0.25411 /
effii      / 0.23888 /
effiii      / 0.08512 /
effiv      / 0.03349 /
ex65U      / 0.26072 /
ex66U      / 0.26031 /
ex67U      / 0.47547 /
ex68U      / 0.26169 /
ex71U      / 0.13257 /
;

VARIABLES
ObjVar Objective function using ' ' algorithm;

SETS
J_Cp /a1,a2,a3,a4,a5/
COMP1 /so2, so3, o2, n2/
J_H2 /a11,a12,a13,a14,a15/
COMP /Sulfur/
j /1,2,3,4,5/
i /I, II, III, IV/
;
 TABLE Coe_Cp(COMP1,J_Cp)
                a1            a2             a3             a4
so2              3.2665         5.3238e-3      6.8437e-7       -5.2810e-9
so3              2.5780         1.4556e-2      -9.1764e-6      -7.9203e-10
o2              3.78246         -2.9967e-3      9.8474e-6       -9.6813e-9
n2              3.5310         -1.2366e-4     -5.0300e-7      2.4353e-9
+               a5
so2              2.55905e-12
so3              1.97095e-12
o2              3.2437e-12
n2              -1.4088e-12

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TABLE Coe_H1(COMP1,J_H2)
                a11           a12            a13            a14
so2              3.2665         5.3238e-3      6.8438e-7       -5.2810e-9
so3              2.5780         1.4556e-2      -9.1764e-6      -7.9203e-10
o2              3.78246         -2.9967e-3      9.8474e-6       -9.6813e-9
n2              3.5310         -1.2366e-4     -5.0300e-7      2.4353e-9
+               a15
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241  so2            2.5591e-12
242  so3            1.9710e-12
243  o2             3.2437e-12
244  n2             -1.4088e-12
245  TABLE Coe_H2(COMP1,J_H2)
246                a11          a12          a13          a14
247  so2            5.2451       1.9704e-3    -8.0376e-7   1.5150e-10
248  so3            7.0757       3.1763e-3    -1.3536e-6   2.5631e-10
249  o2             3.6610       6.5637e-4    -1.4115e-7   2.0580e-11
250  n2             2.9526       1.3969e-3    -4.9263e-7   7.8601e-11
251  +              a15
252  so2            1.0558e-14
253  so3            -1.7936e-14
254  o2             -1.2991e-15
255  n2             -4.60755e-15
256   TABLE Coe_HS(COMP,J_H2)
257                a11          a12          a13          a14
258  Sulfur         3.5008       3.8166e-4    -1.5557e-7   2.7278e-11
259  +              a15
260  Sulfur         -1.7281e-15
261   TABLE pres(i,j)
262                1            2            3            4
263  I              1.391        1.3695       1.348        1.3265
264  II             1.295        1.2925       1.2900       1.2875
265  III            1.263        1.2581       1.2532       1.2483
266  IV             1.0934       1.0884875    1.083575     1.0786625
267  +              5
268  I              1.305
269  II             1.285
270  III            1.2434
271  IV             1.07375
272
273  EQUATIONS
274  * The Constraints
275  EQU1, EQU2, EQU3, EQU4, EQU5, EQU6,
276  EQU7, EQU8, EQU9, EQU10, EQU11, EQU12,
277  EQU13, EQU14, EQU15, EQU16, EQU17, EQU18,
278  EQU19, EQU20, EQU21, EQU22, EQU23, EQU24,
279  EQU25, EQU26, EQU27, EQU28, EQU29, EQU30,

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281  EQU37, EQU38, EQU39, EQU40, EQU41, EQU42,
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325  EQU301, EQU302, EQU303, EQU304, EQU305, EQU306,

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 402  EQU763, EQU764, EQU765,
 403  ObjName;
 404
 405  ObjName..ObjVar=E=
 406  profit;
 407
 408  EQU1..f06 =e= f06O2+f06N2;
 409  EQU2..H06 =e= R*( f06O2*(SUM(J_H2,Coe_H1("O2",J_H2)/ORD(J_H2)* POWER(T06, ORD(J_H2))) +b1_O2- H298_O2) + f06N2*(SUM(J_H2,
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                                      Coe_H1("N2",J_H2)/ORD(J_H2)* POWER(T06, ORD(J_H2))) + b1_N2- H298_N2) );
 410  EQU3..f08SO2 =e= f09SO2;
 411  EQU4..f09 =e= f09O2+f09N2+f09SO2+f09SO3;
 412  EQU5..BLRdT =e= ( T08+T09)/2 - ( (Tsw1a-32)/1.8+273.15 + (Tss1a-32)/1.8+273.15) /2;
 413  EQU6..(H08-H09) - BLRArea*BLRU*BLRdT =e= 0;
 414  EQU7..Hss1a+H09 + BLRloss-(Hsw1a+H08) =e= 0;
 415  EQU8..Hss1a=e=fss1a*factor2*(1-bdfrac)*(5.3266*Tss1a-0.2839*Pss1a-7.3524e-3*Tss1a**2+3.5815e-6*Tss1a**3 -7.2892e-5*Pss1a**2+4.
      5954e-4*Tss1a*Pss1a)+fss1a*factor2*bdfrac*(1.0862*Tss1a-5.6313e-4*Tss1a**2+8.3449e-7*Tss1a**3-1.1427e4/Tss1a+1.0182e6/Tss1a**2

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                                                                      );
 416  EQU9..H09 =e= R*( f09O2* (SUM(J_H2,1/ORD(J_H2)*Coe_H1("O2",J_H2)* POWER(T09, ORD(J_H2) ) ) - H298_O2+b1_O2) +
 417    f09N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(T09, ORD(J_H2) ) ) - H298_N2+b1_N2)  +
 418    f09SO2*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T09, ORD(J_H2) ) ) - H298_SO2+b1_SO2)  +
 419    f09SO3*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(T09, ORD(J_H2) ) ) - H298_SO3+b1_SO3)  );
 420  EQU10..f08N2 =e= f09N2;
 421  EQU11..f08O2 =e= f09O2;
 422  EQU12..f08SO3 =e= f09SO3;
 423  EQU13..fsw1a =e= fss1a;
 424  EQU14..HrSO3 =e= -Factor1*1.827*(-24097-0.26*T07+1.69e-3*T07**2 +1.5e5/T07 );
 425  EQU15..H07=e=  R*( f07O2* (SUM(J_H2,Coe_H2("O2",J_H2)/ORD(J_H2)* POWER(T07, ORD(J_H2)))
 426  + b2_O2 - H298_O2) +f07N2* (SUM(J_H2,Coe_H2("N2",J_H2)/ORD(J_H2)* POWER(T07, ORD(J_H2)))
 427  + b2_N2 - H298_N2) + f07SO2*(SUM(J_H2,Coe_H2("SO2",J_H2)/ORD(J_H2)* POWER(T07, ORD(J_H2)))
 428  +b2_SO2- H298_SO2) + f07SO3*( SUM(J_H2,Coe_H2("SO3",J_H2)/ORD(J_H2)* POWER(T07, ORD(J_H2)))
 429  +b2_SO3- H298_SO3) );
 430  EQU16..f07O2 =e= f06O2-f50*1.01;
 431  EQU17..f07N2 =e= f06N2;
 432  EQU18..f07SO2 =e= 0.98*f50;
 433  EQU19..H50 =e= f50*4.0758;
 434  EQU20..f07 =e= f07O2+f07N2+f07SO2+f07SO3;
 435  EQU21..H07-H06-H50-f50*(HrSO2 + 0.02*HrSO3) +frnloss =E= 0;
 436  EQU22..f07SO3 =e= 0.02*f50;
 437  EQU23..HrSO2 =e= R*( SUM(J_H2,Coe_H2("O2",J_H2)/ORD(J_H2)*POWER(T07, ORD(J_H2) ) )+b2_O2
 438   +SUM(J_H2,Coe_HS("Sulfur",J_H2)/ORD(J_H2)*POWER(T07, ORD(J_H2) ) )+b2_S
 439   -SUM(J_H2,Coe_H2("SO2",J_H2)/ORD(J_H2)*POWER(T07, ORD(J_H2)) )-b2_SO2    );
 440  EQU24..f15so3=e= f14so3;
 441  EQU25..f15 =e= f15o2 +f15n2 + f15so2 + f15so3;
 442  EQU26..Ex65DT =e= (T14-T16 + T15-T19 )/2.0;
 443  EQU27..H15+H19-H14-H16 + ex65loss  =E= 0;
 444  EQU28..f19so2=e= f16so2;
 445  EQU29..f19n2 =e= f16n2;
 446  EQU30..f16 =e= f16o2 +f16n2 + f16so2;
 447  EQU31..H16=E=R*( f16O2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)* POWER(T16,ORD(J_H2)))- H298_O2+b1_O2) +
 448       f16N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(T16,ORD(J_H2))) - H298_N2 +b1_N2) +
 449       f16SO2*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(T16,ORD(J_H2))) - H298_SO2+b1_SO2) );
 450  EQU32..H14- H15 -ex65area*ex65U*ex65dt =e=0;
 451  EQU33..f15so2=e= f14so2;
 452  EQU34..f15n2=e=f14n2;
 453  EQU35..f15o2=e=f14o2;
 454  EQU36..H15=E=R*( f15O2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(T15,ORD(J_H2))) - H298_O2+b1_O2) +
 455       f15N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(T15,ORD(J_H2)))    - H298_N2 +b1_N2) +
 456       f15SO2*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T15,ORD(J_H2)))  - H298_SO2+b1_SO2) +
 457       f15SO3*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(T15,ORD(J_H2))) - H298_SO3 +b1_SO3) );
 458  EQU37..f19o2=e=f16o2;
 459  EQU38..f06O2 / f06N2 =e= 0.21/0.79;
 460    EQU39..fsw1a/fsw1 =e= wbratio;

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 461  EQU40..emiss1=e=(f25so2*64.0*2.204)/(ffprod*( Xprod*so3+(1-Xprod)*h2o) /1);
 462  EQU41..(f15SO3 + f24SO3)/ffprod =e= Xprod;
 463  EQU42..fdw =e= ffprod*(1-Xprod);
 464  EQU43..Pss1a =e= Pss1b;
 465  EQU44..fss2 =e= fss4 + fss5;
 466  EQU45..Tss1a =e= Tss1b;
 467  EQU46..Pss1 =e= Pss1a;
 468  EQU47..CLRdT =e= ( T11+T12)/2 - ( (Tsw1b-32)/1.8+273.15 + (Tss1b-32)/1.8+273.15) /2;
 469  EQU48..(H11-H12) - CLRArea*CLRU*CLRdT =e= 0;
 470  EQU49..Hss1b+H12 + CLRloss-(Hsw1b+H11) =e= 0;
 471  EQU50..Hss1b=e=fss1b*factor2*(1-bdfrac)*(5.3266*Tss1b-0.2839*Pss1b-7.3524e-3*Tss1b**2+3.5815e-6*Tss1b**3-7.2892e-5*Pss1b**2+4.
      5954e-4*Tss1b*Pss1b)+fss1b*factor2*bdfrac*(1.0862*Tss1b-5.6313e-4*Tss1b**2+8.3449e-7*Tss1b**3-1.1427e4/Tss1b+1.0182e6/Tss1b**2
                                                                      );
 472  EQU51..H12 =e= R*( f12O2* (SUM(J_H2,1/ORD(J_H2)*Coe_H1("O2",J_H2)* POWER(T12, ORD(J_H2) ) ) - H298_O2+b1_O2) +
 473    f12N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(T12, ORD(J_H2) ) ) - H298_N2+b1_N2)  +
 474    f12SO2*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T12, ORD(J_H2) ) ) - H298_SO2+b1_SO2)  +
 475    f12SO3*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(T12, ORD(J_H2) ) ) - H298_SO3+b1_SO3)  );
 476  EQU52..f11SO3 =e= f12SO3;
 477  EQU53..f11 =e= f11o2 + f11n2 +f11so2 +f11so3;
 478  EQU54..f11O2 =e= f12O2;
 479  EQU55..fsw1b =e= fss1b;
 480  EQU56..f11N2 =e= f12N2;
 481  EQU57..f12 =e= f12o2 + f12n2 +f12so2 +f12so3;
 482  EQU58..f11SO2 =e= f12SO2;
 483  EQU59..tfi2 =e= tfi1+.5*(fiSO22-fiSO21);
 484  EQU60..fiO21 =e= f10O2;
 485  EQU61..Ftrin22 =e=1.058*Trin22**.645 - .261/( (1.9* Trin22)**(.9*log10(1.9*Trin22)) );
 486  EQU62..Ftrin23 =e=1.058*Trin23**.645 - .261/( (1.9* Trin23)**(.9*log10(1.9*Trin23)) );
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EQU63..Ftrin24 =e=1.058*Trin24**.645 - .261/( (1.9* Trin24)**(.9*log10(1.9*Trin24)) );
EQU64..Ftrin25 =e=1.058*Trin25**.645 - .261/( (1.9* Trin25)**(.9*log10(1.9*Trin25)) );
EQU65..FtriSO22 =e=1.058*TriSO22**.645 - .261/( (1.9* TriSO22)**(.9*log10(1.9*TriSO22)) );
EQU66..FtriO25 =e=1.058*TriO25**.645 - .261/( (1.9* TriO25)**(.9*log10(1.9*TriO25)) );
EQU67..FtriSO23 =e=1.058*TriSO23**.645 - .261/( (1.9* TriSO23)**(.9*log10(1.9*TriSO23)) );
EQU68..FtriSO24 =e=1.058*TriSO24**.645 - .261/( (1.9* TriSO24)**(.9*log10(1.9*TriSO24)) );
EQU69..FtriSO25 =e=1.058*TriSO25**.645 - .261/( (1.9* TriSO25)**(.9*log10(1.9*TriSO25)) );
EQU70..fiSO21 =e= f10SO2;
EQU71..fiSO25 =e= fiSO24+h1*ffiSO24;
EQU72..fiSO24 =e= fiSO23+h1*ffiSO23;
EQU73..FtriSO31 =e=1.058*TriSO31**.645 - .261/( (1.9* TriSO31)**(.9*log10(1.9*TriSO31)) );
EQU74..FtriSO21 =e=1.058*TriSO21**.645 - .261/( (1.9* TriSO21)**(.9*log10(1.9*TriSO21)) );
EQU75..TriSO33 =e= Tgasi3/ct_SO3;
EQU76..TriSO22 =e= Tgasi2/ct_SO2;
EQU77..tfi5 =e= tfi4+.5*(fiSO25-fiSO24);
EQU78..tfi4 =e= tfi3+.5*(fiSO24-fiSO23);
EQU79..mwprod =e= Xprod*so3 + (1-Xprod)*h2o;
EQU80..profit =e= ffprod*mwprod*cstacid + (fshp1+fshp2)* csthpsteam - f50*cstsulfur - fsbfw*cstfeedw - fdw*cstdilutw;

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EQU81..Tss1 =e=  Tss1a;
EQU82..Pss2 =e= Pss1;
EQU83..so2ppm1 =e= so2ppm/1000;
EQU84..emiss1 =e= emiss/1000;
EQU85..fprod =e= ffprod*mwprod;
EQU86..TriSO23=e= Tgasi3/ct_SO2;
EQU87..TriSO24 =e= Tgasi4/ct_SO2;
EQU88..TriSO25 =e= Tgasi5/ct_SO2;
EQU89..Ftrin21 =e=1.058*Trin21**.645 - .261/( (1.9* Trin21)**(.9*log10(1.9*Trin21)) );
EQU90..TriSO32 =e= Tgasi2/ct_SO3;
EQU91..tfi3 =e= tfi2+.5*(fiSO23-fiSO22);
EQU92..TriSO34 =e= Tgasi4/ct_SO3;
EQU93..TriSO35 =e= Tgasi5/ct_SO3;
EQU94..FtriO21 =e=1.058*TriO21**.645 - .261/( (1.9* TriO21)**(.9*log10(1.9*TriO21)) );
EQU95..FtriO22 =e=1.058*TriO22**.645 - .261/( (1.9* TriO22)**(.9*log10(1.9*TriO22)) );
EQU96..FtriO23 =e=1.058*TriO23**.645 - .261/( (1.9* TriO23)**(.9*log10(1.9*TriO23)) );
EQU97..FtriO24 =e=1.058*TriO24**.645 - .261/( (1.9* TriO24)**(.9*log10(1.9*TriO24)) );
EQU98..FtriSO34 =e=1.058*TriSO34**.645 - .261/( (1.9* TriSO34)**(.9*log10(1.9*TriSO34)) );
EQU99..TriSO31 =e= Tgasi1/ct_SO3;
EQU100..di1201 =e= exp(-8.59+7020/Tcati1);
EQU101..ffiSO22 =e= -(1.2583e-4)/2 *(ratei3+ratei2)*Area*BD120;
EQU102..ai1204 =e= exp(-5.69+4060/Tcati4);
EQU103..ai1205 =e= exp(-5.69+4060/Tcati5);
EQU104..ci1201 =e= exp(6.45-4610/Tcati1);
EQU105..ci1202 =e= exp(6.45-4610/Tcati2);
EQU106..ci1203 =e= exp(6.45-4610/Tcati3);
EQU107..FtriSO32 =e=1.058*TriSO32**.645 - .261/( (1.9* TriSO32)**(.9*log10(1.9*TriSO32)) );
EQU108..ci1205 =e= exp(6.45-4610/Tcati5);
EQU109..ai1202 =e= exp(-5.69+4060/Tcati2);
EQU110..ffiSO21 =e= -(1.2583e-4)/2 *(ratei2+ratei1)*Area*BD120;
EQU111..di1202 =e= exp(-8.59+7020/Tcati2);
EQU112..di1203 =e= exp(-8.59+7020/Tcati3);
EQU113..di1204 =e= exp(-8.59+7020/Tcati4);
EQU114..di1205 =e= exp(-8.59+7020/Tcati5);
EQU115..Kpi1   =e= 10**(5129/Tcati1-4.869);
EQU116..Kpi2   =e= 10**(5129/Tcati2-4.869);
EQU117..ci1204 =e= exp(6.45-4610/Tcati4);
EQU118..rateinti3 =e=( ((pres("i","3")/F10)**1.5) *f10SO2*(f10O2**.5) ) /( Ai1203+ci1203*( f10SO2/F10*pres("i","3") )
          +di1203*(pres("i","3")*fiSO33/tfi3) )**2*( 1-fiSO33/( kpi3*fiSO23*(pres("i","3")*fiO23/tfi3)**.5 ) );
EQU119..Trin24 =e= Tgasi4/ct_n2;
EQU120..FtriSO35 =e=1.058*TriSO35**.645 - .261/( (1.9* TriSO35)**(.9*log10(1.9*TriSO35)) );
EQU121..ratei1 =e= rateinti1*effi;
EQU122..ratei2 =e= rateinti2*effi;
EQU123..ratei3 =e= rateinti3*effi;
EQU124..ratei4 =e= rateinti4*effi;
  EQU125..ratei5 =e= rateinti5*effi;

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EQU126..ffiSO23 =e= -(1.2583e-4)/2 *(ratei4+ratei3)*Area*BD120;
EQU127..rateinti2 =e=( ((pres("i","2")/F10)**1.5) *f10SO2*(f10O2**.5) ) /( Ai1202+ci1202*( f10SO2/F10*pres("i","2") )
          +di1202*(pres("i","2")*fiSO32/tfi2) )**2*( 1-fiSO32/( kpi2*fiSO22*(pres("i","2")*fiO22/tfi2)**.5 ) );
EQU128..ai1203 =e= exp(-5.69+4060/Tcati3);
EQU129..rateinti4 =e=( ((pres("i","4")/F10)**1.5) *f10SO2*(f10O2**.5) ) /( Ai1204+ci1204*( f10SO2/F10*pres("i","4") )
          +di1204*(pres("i","4")*fiSO34/tfi4) )**2*( 1-fiSO34/( kpi4*fiSO24*(pres("i","4")*fiO24/tfi4)**.5 ) );
EQU130..fiSO23 =e= fiSO22+h1*ffiSO22;
EQU131..rateinti5 =e=( ((pres("i","5")/F10)**1.5) *f10SO2*(f10O2**.5) ) /( Ai1205+ci1205*( f10SO2/F10*pres("i","5") )
          +di1205*(pres("i","5")*fiSO35/tfi5) )**2*( 1-fiSO35/( kpi5*fiSO25*(pres("i","5")*fiO25/tfi5)**.5 ) );
EQU132..thhii1 =e=(1/3600)/2*( rateii1*Area*bd120*rheatii1+rateii2*Area*bd120*rheatii2 );
EQU133..thhii2 =e=(1/3600)/2*( rateii2*Area*bd120*rheatii2+rateii3*Area*bd120*rheatii3 );
EQU134..thhii3 =e=(1/3600)/2*( rateii3*Area*bd120*rheatii3+rateii4*Area*bd120*rheatii4 );
EQU135..thhii4 =e=(1/3600)/2*( rateii4*Area*bd120*rheatii4+rateii5*Area*bd120*rheatii5 );
EQU136..enthii2 =e= enthii1+h2*thhii1;
EQU137..enthii3 =e= enthii2+h2*thhii2;
EQU138..enthii4 =e= enthii3+h2*thhii3;
EQU139..enthii5 =e= enthii4+h2*thhii4;
EQU140..enthii2=e=R*(fiiO22*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasii2,ORD(J_H2) ) ) - H298_O2+b1_O2)+ f12N2*
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                                   (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasii2,ORD(J_H2) ) ) - H298_N2 +b1_N2)+
  fiiSO22*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasii2,ORD(J_H2) ) ) - H298_SO2+b1_SO2)+
  fiiSO32* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)*POWER(Tgasii2,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
EQU141..enthii3=e=R*(fiiO23*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasii3,ORD(J_H2) ) ) - H298_O2+b1_O2)+ f12N2*
                                   (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasii3,ORD(J_H2) ) ) - H298_N2 +b1_N2)+
  fiiSO23*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasii3,ORD(J_H2) ) ) - H298_SO2+b1_SO2)+
  fiiSO33* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)*POWER(Tgasii3,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
EQU142..enthii4=e=R*(fiiO24*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasii4,ORD(J_H2) ) ) - H298_O2+b1_O2)+ f12N2*
                                   (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasii4,ORD(J_H2) ) ) - H298_N2 +b1_N2)+
  fiiSO24*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasii4,ORD(J_H2) ) ) - H298_SO2+b1_SO2)+
  fiiSO34* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)*POWER(Tgasii4,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
EQU143..enthii5=e=R*(fiiO25*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasii5,ORD(J_H2) ) ) - H298_O2+b1_O2)+ f12N2*
                                   (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasii5,ORD(J_H2) ) ) - H298_N2 +b1_N2)+
  fiiSO25*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasii5,ORD(J_H2) ) ) - H298_SO2+b1_SO2)+
  fiiSO35* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)*POWER(Tgasii5,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
EQU144..Tgasii1 =e= T12;
EQU145..Tcatii1 =e= Tgasii1+dtii1;
EQU146..Tcatii2 =e= Tgasii2+dtii2;
EQU147..Tcatii3 =e= Tgasii3+dtii3;
EQU148..Tcatii4 =e= Tgasii4+dtii4;
EQU149..Tcatii5 =e= Tgasii5+dtii5;
EQU150..dtii1 =e=1/3600*rateii1*rheatii1*BD120*(Pr**0.6667)/(av120*phio*Cpii1*tfii1/area*jhii1);
EQU151..dtii2 =e=1/3600*rateii2*rheatii2*BD120*(Pr**0.6667)/(av120*phio*Cpii2*tfii2/area*jhii2);
EQU152..dtii3 =e=1/3600*rateii3*rheatii3*BD120*(Pr**0.6667)/(av120*phio*Cpii3*tfii3/area*jhii3);
EQU153..dtii4 =e=1/3600*rateii4*rheatii4*BD120*(Pr**0.6667)/(av120*phio*Cpii4*tfii4/area*jhii4);
EQU154..dtii5 =e=1/3600*rateii5*rheatii5*BD120*(Pr**0.6667)/(av120*phio*Cpii5*tfii5/area*jhii5);
EQU155..rheatii1 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcatii1+(1.69e-3)*Tcatii1**2+1.5e5/Tcatii1 );
EQU156..rheatii2 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcatii2+(1.69e-3)*Tcatii2**2+1.5e5/Tcatii2 );
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EQU157..rheatii3 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcatii3+(1.69e-3)*Tcatii3**2+1.5e5/Tcatii3 );
EQU158..rheatii4 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcatii4+(1.69e-3)*Tcatii4**2+1.5e5/Tcatii4 );
EQU159..rheatii5 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcatii5+(1.69e-3)*Tcatii5**2+1.5e5/Tcatii5 );
EQU160..Cpii1 =e= R/tfii1*(fiiO21*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasii1, (ORD(J_Cp)-1) ) )  )  +
  f12n2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)*POWER(Tgasii1, (ORD(J_Cp)-1) ) )  ) +
  fiiSO21*(SUM(J_Cp,Coe_CP("SO2",J_Cp)*POWER(Tgasii1, (ORD(J_Cp)-1) ) )  )  +
  fiiSO31*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*POWER(Tgasii1, (ORD(J_Cp)-1) ) )  )  );
EQU161..Cpii2 =e= R/tfii2*(fiiO22*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasii2, (ORD(J_Cp)-1) ) )  )  +
  f12n2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)*POWER(Tgasii2, (ORD(J_Cp)-1) ) )  ) +
  fiiSO22*(SUM(J_Cp,Coe_CP("SO2",J_Cp)*POWER(Tgasii2, (ORD(J_Cp)-1) ) )  )  +
  fiiSO32*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*POWER(Tgasii2, (ORD(J_Cp)-1) ) )  )  );
EQU162..Cpii3 =e= R/tfii3*(fiiO23*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasii3, (ORD(J_Cp)-1) ) )  )  +
  f12n2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)*POWER(Tgasii3, (ORD(J_Cp)-1) ) )  ) +
  fiiSO23*(SUM(J_Cp,Coe_CP("SO2",J_Cp)*POWER(Tgasii3, (ORD(J_Cp)-1) ) )  )  +
  fiiSO33*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*POWER(Tgasii3, (ORD(J_Cp)-1) ) )  )  );
EQU163..Cpii4 =e= R/tfii4*(fiiO24*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasii4, (ORD(J_Cp)-1) ) )  )  +
  f12n2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)*POWER(Tgasii4, (ORD(J_Cp)-1) ) )  ) +
  fiiSO24*(SUM(J_Cp,Coe_CP("SO2",J_Cp)*POWER(Tgasii4, (ORD(J_Cp)-1) ) )  )  +
  fiiSO34*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*POWER(Tgasii4, (ORD(J_Cp)-1) ) )  )  );
EQU164..Cpii5 =e= R/tfii5*(fiiO25*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasii5, (ORD(J_Cp)-1) ) )  )  +
  f12n2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)*POWER(Tgasii5, (ORD(J_Cp)-1) ) )  ) +
  fiiSO25*(SUM(J_Cp,Coe_CP("SO2",J_Cp)*POWER(Tgasii5, (ORD(J_Cp)-1) ) )  )  +
  fiiSO35*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*POWER(Tgasii5, (ORD(J_Cp)-1) ) )  )  );
EQU165..Mfii1 =e= 7934.4/area*( fiio21*32+fiiso21*64+f12n2*28+fiiso31*80 );
EQU166..Mfii2 =e= 7934.4/area*( fiio22*32+fiiso22*64+f12n2*28+fiiso32*80 );
EQU167..Mfii3 =e= 7934.4/area*( fiio23*32+fiiso23*64+f12n2*28+fiiso33*80 );
EQU168..Mfii4 =e= 7934.4/area*( fiio24*32+fiiso24*64+f12n2*28+fiiso34*80 );
EQU169..Mfii5 =e= 7934.4/area*( fiio25*32+fiiso25*64+f12n2*28+fiiso35*80 );
EQU170..jhii1 =e= 0.91*(Mfii1/av120/phio/Viscii1)**(-.51);
EQU171..jhii2 =e= 0.91*(Mfii2/av120/phio/Viscii2)**(-.51);
EQU172..jhii3 =e= 0.91*(Mfii3/av120/phio/Viscii3)**(-.51);
EQU173..jhii4 =e= 0.91*(Mfii4/av120/phio/Viscii4)**(-.51);
EQU174..jhii5 =e= 0.91*(Mfii5/av120/phio/Viscii5)**(-.51);
EQU175..Viscii1 =e= ( Viscc_o2*Ftriio21*fiio21 + Viscc_so2*Ftriiso21*fiiso21+ Viscc_so3*Ftriiso31*fiiso31+ Viscc_n2*Ftriin21*f
                                                                                   12n2 )/tfii1;
EQU176..Viscii2 =e= ( Viscc_o2*Ftriio22*fiio22 + Viscc_so2*Ftriiso22*fiiso22+ Viscc_so3*Ftriiso32*fiiso32+ Viscc_n2*Ftriin22*f
                                                                                   12n2 )/tfii2;
EQU177..Viscii3 =e= ( Viscc_o2*Ftriio23*fiio23 + Viscc_so2*Ftriiso23*fiiso23+ Viscc_so3*Ftriiso33*fiiso33+ Viscc_n2*Ftriin23*f
                                                                                   12n2 )/tfii3;
EQU178..Viscii4 =e= ( Viscc_o2*Ftriio24*fiio24 + Viscc_so2*Ftriiso24*fiiso24+ Viscc_so3*Ftriiso34*fiiso34+ Viscc_n2*Ftriin24*f
                                                                                   12n2 )/tfii4;
EQU179..Viscii5 =e= ( Viscc_o2*Ftriio25*fiio25 + Viscc_so2*Ftriiso25*fiiso25+ Viscc_so3*Ftriiso35*fiiso35+ Viscc_n2*Ftriin25*f
                                                                                   12n2 )/tfii5;
EQU180..Triio21 =e= Tgasii1/ct_o2;
EQU181..Triio22 =e= Tgasii2/ct_o2;
 EQU182..Triio23 =e= Tgasii3/ct_o2;
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EQU183..Triio24 =e= Tgasii4/ct_o2;
EQU184..Triio25 =e= Tgasii5/ct_o2;
EQU185..Triin21 =e= Tgasii1/ct_n2;
EQU186..Triin22 =e= Tgasii2/ct_n2;
EQU187..Triin23 =e= Tgasii3/ct_n2;
EQU188..Triin24 =e= Tgasii4/ct_n2;
EQU189..Triin25 =e= Tgasii5/ct_n2;
EQU190..Triiso21 =e= Tgasii1/ct_so2;
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642  EQU191..Triiso22 =e= Tgasii2/ct_so2;
643  EQU192..Triiso23 =e= Tgasii3/ct_so2;
644  EQU193..Triiso24 =e= Tgasii4/ct_so2;
645  EQU194..Triiso25 =e= Tgasii5/ct_so2;
646  EQU195..Triiso31 =e= Tgasii1/ct_so3;
647  EQU196..Triiso32 =e= Tgasii2/ct_so3;
648  EQU197..Triiso33 =e= Tgasii3/ct_so3;
649  EQU198..Triiso34 =e= Tgasii4/ct_so3;
650  EQU199..Triiso35 =e= Tgasii5/ct_so3;
651  EQU200..Ftriio21 =e=1.058*Triio21**.645 - .261/( (1.9*Triio21)**(.9*log10(1.9*Triio21)) );
652  EQU201..Ftriio22 =e=1.058*Triio22**.645 - .261/( (1.9*Triio22)**(.9*log10(1.9*Triio22)) );
653  EQU202..Ftriio23 =e=1.058*Triio23**.645 - .261/( (1.9*Triio23)**(.9*log10(1.9*Triio23)) );
654  EQU203..Ftriio24 =e=1.058*Triio24**.645 - .261/( (1.9*Triio24)**(.9*log10(1.9*Triio24)) );
655  EQU204..Ftriio25 =e=1.058*Triio25**.645 - .261/( (1.9*Triio25)**(.9*log10(1.9*Triio25)) );
656  EQU205..Ftriin21 =e=1.058*Triin21**.645 - .261/( (1.9*Triin21)**(.9*log10(1.9*Triin21)) );
657  EQU206..Ftriin22 =e=1.058*Triin22**.645 - .261/( (1.9*Triin22)**(.9*log10(1.9*Triin22)) );
658  EQU207..Ftriin23 =e=1.058*Triin23**.645 - .261/( (1.9*Triin23)**(.9*log10(1.9*Triin23)) );
659  EQU208..Ftriin24 =e=1.058*Triin24**.645 - .261/( (1.9*Triin24)**(.9*log10(1.9*Triin24)) );
660  EQU209..Ftriin25 =e=1.058*Triin25**.645 - .261/( (1.9*Triin25)**(.9*log10(1.9*Triin25)) );
661  EQU210..Ftriiso21 =e=1.058*Triiso21**.645 - .261/( (1.9*Triiso21)**(.9*log10(1.9*Triiso21)) );
662  EQU211..Ftriiso22 =e=1.058*Triiso22**.645 - .261/( (1.9*Triiso22)**(.9*log10(1.9*Triiso22)) );
663  EQU212..Ftriiso23 =e=1.058*Triiso23**.645 - .261/( (1.9*Triiso23)**(.9*log10(1.9*Triiso23)) );
664  EQU213..Ftriiso24 =e=1.058*Triiso24**.645 - .261/( (1.9*Triiso24)**(.9*log10(1.9*Triiso24)) );
665  EQU214..Ftriiso25 =e=1.058*Triiso25**.645 - .261/( (1.9*Triiso25)**(.9*log10(1.9*Triiso25)) );
666  EQU215..Ftriiso31 =e=1.058*Triiso31**.645 - .261/( (1.9*Triiso31)**(.9*log10(1.9*Triiso31)) );
667  EQU216..Ftriiso32 =e=1.058*Triiso32**.645 - .261/( (1.9*Triiso32)**(.9*log10(1.9*Triiso32)) );
668  EQU217..Ftriiso33 =e=1.058*Triiso33**.645 - .261/( (1.9*Triiso33)**(.9*log10(1.9*Triiso33)) );
669  EQU218..Ftriiso34 =e=1.058*Triiso34**.645 - .261/( (1.9*Triiso34)**(.9*log10(1.9*Triiso34)) );
670  EQU219..Ftriiso35 =e=1.058*Triiso35**.645 - .261/( (1.9*Triiso35)**(.9*log10(1.9*Triiso35)) );
671  EQU220..rateii1 =e= rateintii1*effii;
672  EQU221..rateii2 =e= rateintii2*effii;
673  EQU222..rateii3 =e= rateintii3*effii;
674  EQU223..rateii4 =e= rateintii4*effii;
675  EQU224..rateii5 =e= rateintii5*effii;
676  EQU225..rateintii1=e= ( ((pres("ii","1")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aii1201+cii1201*(f10so2/f10*pres("ii","1"))
677            +dii1201*(pres("ii","1")*fiiso31/tfii1) )**2 *( 1-fiiso31/( kpii1*fiiso21* (pres("ii","1")*fiio21/tfii1)**.5 ) );
678  EQU226..rateintii2=e= ( ((pres("ii","2")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aii1202+cii1202*(f10so2/f10*pres("ii","2"))
679               +dii1202*(pres("ii","2")*fiiso32/tfii2) )**2 *( 1-fiiso32/( kpii2*fiiso22* (pres("ii","2")*fiio22/tfii2)**.5 ) );

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680  EQU227..rateintii3=e= ( ((pres("ii","3")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aii1203+cii1203*(f10so2/f10*pres("ii","3"))
681            +dii1203*(pres("ii","3")*fiiso33/tfii3) )**2 *( 1-fiiso33/( kpii3*fiiso23* (pres("ii","3")*fiio23/tfii3)**.5 ) );
682  EQU228..rateintii4=e= ( ((pres("ii","4")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aii1204+cii1204*(f10so2/f10*pres("ii","4"))
683            +dii1204*(pres("ii","4")*fiiso34/tfii4) )**2 *( 1-fiiso34/( kpii4*fiiso24* (pres("ii","4")*fiio24/tfii4)**.5 ) );
684  EQU229..rateintii5=e= ( ((pres("ii","5")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aii1205+cii1205*(f10so2/f10*pres("ii","5"))
685            +dii1205*(pres("ii","5")*fiiso35/tfii5) )**2 *( 1-fiiso35/( kpii5*fiiso25* (pres("ii","5")*fiio25/tfii5)**.5 ) );
686  EQU230..aii1201 =e= exp(-5.69+4060/Tcatii1);
687  EQU231..aii1202 =e= exp(-5.69+4060/Tcatii2);
688  EQU232..aii1203 =e= exp(-5.69+4060/Tcatii3);
689  EQU233..aii1204 =e= exp(-5.69+4060/Tcatii4);
690  EQU234..aii1205 =e= exp(-5.69+4060/Tcatii5);
691  EQU235..cii1201 =e= exp(6.45-4610/Tcatii1);
692  EQU236..cii1202 =e= exp(6.45-4610/Tcatii2);
693  EQU237..cii1203 =e= exp(6.45-4610/Tcatii3);
694  EQU238..cii1204 =e= exp(6.45-4610/Tcatii4);
695  EQU239..cii1205 =e= exp(6.45-4610/Tcatii5);
696  EQU240..dii1201 =e= exp(-8.59+7020/Tcatii1);
697  EQU241..dii1202 =e= exp(-8.59+7020/Tcatii2);
698  EQU242..dii1203 =e= exp(-8.59+7020/Tcatii3);
699  EQU243..dii1204 =e= exp(-8.59+7020/Tcatii4);
700  EQU244..dii1205 =e= exp(-8.59+7020/Tcatii5);
701  EQU245..Kpii1   =e= 10**(5129/Tcatii1-4.869);
702  EQU246..Kpii2   =e= 10**(5129/Tcatii2-4.869);
703  EQU247..Kpii3   =e= 10**(5129/Tcatii3-4.869);
704  EQU248..Kpii4   =e= 10**(5129/Tcatii4-4.869);
705  EQU249..Kpii5   =e= 10**(5129/Tcatii5-4.869);
706  EQU250..f12n2 =e= f13n2;
707  EQU251..fiio25 =e= f13o2;
708  EQU252..fiiso25 =e= f13so2;
709  EQU253..fiiso35 =e= f13so3;
710  EQU254..Tgasii5 =e= T13;
711  EQU255..enthii5 =e= H13;
712  EQU256..fiiio21 =e= f20o2;
713  EQU257..fiiiso21 =e= f20so2;
714  EQU258..fiiiso31 =e= 0;
715  EQU259..ffiiiso21 =e= -(1.2583e-4)/2 *( rateiii2+rateiii1 )*Area*BD110;
716  EQU260..ffiiiso22 =e= -(1.2583e-4)/2 *( rateiii3+rateiii2 )*Area*BD110;
717  EQU261..ffiiiso23 =e= -(1.2583e-4)/2 *( rateiii4+rateiii3 )*Area*BD110;
718  EQU262..ffiiiso24 =e= -(1.2583e-4)/2 *( rateiii5+rateiii4 )*Area*BD110;
719  EQU263..fiiiso22 =e= fiiiso21+h3*ffiiiso21;
720  EQU264..fiiiso23 =e= fiiiso22+h3*ffiiiso22;
721  EQU265..fiiiso24 =e= fiiiso23+h3*ffiiiso23;
722  EQU266..fiiiso25 =e= fiiiso24+h3*ffiiiso24;
723  EQU267..tfiii2 =e= tfiii1 +.5*(fiiiso22-fiiiso21);
724  EQU268..tfiii3 =e= tfiii2 +.5*(fiiiso23-fiiiso22);
725  EQU269..tfiii4 =e= tfiii3 +.5*(fiiiso24-fiiiso23);

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EQU270..tfiii5 =e= tfiii4 +.5*(fiiiso25-fiiiso24);
EQU271..fiiio22 =e= fiiio21 +.5*(fiiiso22-fiiiso21);
EQU272..fiiio23 =e= fiiio22 +.5*(fiiiso23-fiiiso22);
EQU273..fiiio24 =e= fiiio23 +.5*(fiiiso24-fiiiso23);
EQU274..fiiio25 =e= fiiio24 +.5*(fiiiso25-fiiiso24);
EQU275..fiiiso32 =e= fiiiso31- (fiiiso22-fiiiso21);
EQU276..fiiiso33 =e= fiiiso32- (fiiiso23-fiiiso22);
EQU277..fiiiso34 =e= fiiiso33- (fiiiso24-fiiiso23);
EQU278..fiiiso35 =e= fiiiso34- (fiiiso25-fiiiso24);
EQU279..enthiii1 =e= h20;
EQU280..thhiii1 =e= (1/3600)/2*( rateiii1*Area*bd110*rheatiii1+rateiii2*Area*bd110*rheatiii2 );
EQU281..thhiii2 =e= (1/3600)/2*( rateiii2*Area*bd110*rheatiii2+rateiii3*Area*bd110*rheatiii3 );
EQU282..thhiii3 =e= (1/3600)/2*( rateiii3*Area*bd110*rheatiii3+rateiii4*Area*bd110*rheatiii4 );
EQU283..thhiii4 =e= (1/3600)/2*( rateiii4*Area*bd110*rheatiii4+rateiii5*Area*bd110*rheatiii5 );
EQU284..enthiii2 =e= enthiii1+h3*thhiii1;
EQU285..enthiii3 =e= enthiii2+h3*thhiii2;
EQU286..enthiii4 =e= enthiii3+h3*thhiii3;
EQU287..enthiii5 =e= enthiii4+h3*thhiii4;
EQU288..enthiii2=e=R*( fiiiO22*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasiii2,ORD(J_H2) ) )-H298_O2+b1_O2 )+
   f20N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiii2,ORD(J_H2)  ) )  - H298_N2+b1_N2 )  +
   fiiiSO22*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasiii2,ORD(J_H2)  )  )  - H298_SO2+b1_SO2 ) +
   fiiiSO32* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiii2,ORD(J_H2)  )  ) - H298_SO3 +b1_SO3 ) );
EQU289..enthiii3=e=R*( fiiiO23*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasiii3,ORD(J_H2) ) )-H298_O2+b1_O2 )+
   f20N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiii3,ORD(J_H2)  ) )  - H298_N2+b1_N2 )  +
   fiiiSO23*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasiii3,ORD(J_H2)  )  )  - H298_SO2+b1_SO2 ) +
   fiiiSO33* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiii3,ORD(J_H2)  )  ) - H298_SO3 +b1_SO3 ) );
EQU290..enthiii4=e=R*( fiiiO24*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasiii4,ORD(J_H2) ) )-H298_O2+b1_O2 )+
   f20N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiii4,ORD(J_H2)  ) )  - H298_N2+b1_N2 )  +
   fiiiSO24*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasiii4,ORD(J_H2)  )  )  - H298_SO2+b1_SO2 ) +
   fiiiSO34* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiii4,ORD(J_H2)  )  ) - H298_SO3 +b1_SO3 ) );
EQU291..enthiii5=e=R*( fiiiO25*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasiii5,ORD(J_H2) ) )-H298_O2+b1_O2 )+
   f20N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiii5,ORD(J_H2)  ) )  - H298_N2+b1_N2 )  +
   fiiiSO25*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(Tgasiii5,ORD(J_H2)  )  )  - H298_SO2+b1_SO2 ) +
   fiiiSO35* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiii5,ORD(J_H2)  )  ) - H298_SO3 +b1_SO3 ) );
EQU292..Tgasiii1 =e= T20;
EQU293..Tcatiii1 =e= Tgasiii1+dtiii1;
EQU294..Tcatiii2 =e= Tgasiii2+dtiii2;
EQU295..Tcatiii3 =e= Tgasiii3+dtiii3;
EQU296..Tcatiii4 =e= Tgasiii4+dtiii4;
EQU297..Tcatiii5 =e= Tgasiii5+dtiii5;
EQU298..dtiii1 =e= 1/3600*rateiii1*rheatiii1*BD110*(Pr**0.6667) /(av110*phio*Cpiii1*tfiii1/area*jhiii1);
EQU299..dtiii2 =e= 1/3600*rateiii2*rheatiii2*BD110*(Pr**0.6667) /(av110*phio*Cpiii2*tfiii2/area*jhiii2);
EQU300..dtiii3 =e= 1/3600*rateiii3*rheatiii3*BD110*(Pr**0.6667) /(av110*phio*Cpiii3*tfiii3/area*jhiii3);
EQU301..dtiii4 =e= 1/3600*rateiii4*rheatiii4*BD110*(Pr**0.6667) /(av110*phio*Cpiii4*tfiii4/area*jhiii4);
EQU302..dtiii5 =e= 1/3600*rateiii5*rheatiii5*BD110*(Pr**0.6667) /(av110*phio*Cpiii5*tfiii5/area*jhiii5);
EQU303..fiSO22 =e= fiSO21+h1*ffiSO21;
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EQU304..ffiSO24 =e= -(1.2583e-4)/2 *(ratei5+ratei4)*Area*BD120;
EQU305..ai1201 =e= exp(-5.69+4060/Tcati1);
EQU306..FtriSO33 =e=1.058*TriSO33**.645 - .261/( (1.9* TriSO33)**(.9*log10(1.9*TriSO33)) );
EQU307..rateinti1 =e=( ((pres("i","1")/F10)**1.5) *f10SO2*(f10O2**.5) ) /( Ai1201+ci1201*( f10SO2/F10*pres("i","1") )
            +di1201*(pres("i","1")*fiSO31/tfi1) )**2*( 1-fiSO31/( kpi1*fiSO21*(pres("i","1")*fiO21/tfi1)**.5 ) );
EQU308..rheati4 =e=-1.055e-3*1.827*( -24097-0.26*Tcati4+(1.69e-3)*Tcati4**2+1.5e5/Tcati4 );
EQU309..Mfi2 =e= 7934.4/area*(fiO22*32+fiSO22*64+f10n2*28+fiSO32*80 );
EQU310..dti2 =e= 1/3600*ratei2*rheati2*BD120*(Pr**0.6667)/(av120*phio*Cpi2*tfi2/area*jhi2);
EQU311..dti3 =e= 1/3600*ratei3*rheati3*BD120*(Pr**0.6667)/(av120*phio*Cpi3*tfi3/area*jhi3);
EQU312..dti4 =e= 1/3600*ratei4*rheati4*BD120*(Pr**0.6667)/(av120*phio*Cpi4*tfi4/area*jhi4);
EQU313..dti5 =e= 1/3600*ratei5*rheati5*BD120*(Pr**0.6667)/(av120*phio*Cpi5*tfi5/area*jhi5);
EQU314..rheati1 =e=-1.055e-3*1.827*( -24097-0.26*Tcati1+(1.69e-3)*Tcati1**2+1.5e5/Tcati1 );
EQU315..Tcati5=e= Tgasi5+dti5;
EQU316..rheati3 =e=-1.055e-3*1.827*( -24097-0.26*Tcati3+(1.69e-3)*Tcati3**2+1.5e5/Tcati3 );
EQU317..Tcati4=e= Tgasi4+dti4;
EQU318..rheati5 =e=-1.055e-3*1.827*( -24097-0.26*Tcati5+(1.69e-3)*Tcati5**2+1.5e5/Tcati5 );
EQU319..Cpi1 =e=R/tfi1*(fiO21*( SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasi1, (ORD(J_Cp)-1) ) ) ) +
  f10N2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasi1, (ORD(J_Cp)-1) ) ) ) +
  fiSO21*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)* POWER(Tgasi1, (ORD(J_Cp)-1) ) ) ) +
  fiSO31*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)* POWER(Tgasi1, (ORD(J_Cp)-1) ) ) ) );
EQU320..Cpi2 =e=R/tfi2*(fiO22*( SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasi2, (ORD(J_Cp)-1) ) ) ) +
  f10N2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasi2, (ORD(J_Cp)-1) ) ) ) +
  fiSO22*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)* POWER(Tgasi2, (ORD(J_Cp)-1) ) ) ) +
  fiSO32*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)* POWER(Tgasi2, (ORD(J_Cp)-1) ) ) ) );
EQU321..Cpi3 =e=R/tfi3*(fiO23*( SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasi3, (ORD(J_Cp)-1) ) ) ) +
  f10N2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasi3, (ORD(J_Cp)-1) ) ) ) +
  fiSO23*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)* POWER(Tgasi3, (ORD(J_Cp)-1) ) ) ) +
  fiSO33*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)* POWER(Tgasi3, (ORD(J_Cp)-1) ) ) ) );
EQU322..Cpi4 =e=R/tfi4*(fiO24*( SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasi4, (ORD(J_Cp)-1) ) ) ) +
  f10N2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasi4, (ORD(J_Cp)-1) ) ) ) +
  fiSO24*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)* POWER(Tgasi4, (ORD(J_Cp)-1) ) ) ) +
  fiSO34*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)* POWER(Tgasi4, (ORD(J_Cp)-1) ) ) ) );
EQU323..Cpi5 =e=R/tfi5*(fiO25*( SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasi5, (ORD(J_Cp)-1) ) ) ) +
  f10N2*( SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasi5, (ORD(J_Cp)-1) ) ) ) +
  fiSO25*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)* POWER(Tgasi5, (ORD(J_Cp)-1) ) ) ) +
  fiSO35*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)* POWER(Tgasi5, (ORD(J_Cp)-1) ) ) ) );
EQU324..TriSO21 =e= Tgasi1/ct_SO2;
EQU325..rheati2 =e=-1.055e-3*1.827*( -24097-0.26*Tcati2+(1.69e-3)*Tcati2**2+1.5e5/Tcati2 );
EQU326..enthi2 =e=  R*( fiO22*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasi2,ORD(J_H2) ) )- H298_O2+b1_O2 ) +
  f10N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(Tgasi2,ORD(J_H2) ) )  - H298_N2 +b1_N2 ) +
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812    fiSO22*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasi2,ORD(J_H2) ) )  - H298_SO2+b1_SO2 ) +
813    fiSO32* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasi2,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
814  EQU327..thhi1 =e= (1/3600)/2*(ratei1*Area*bd120*rheati1+ratei2*Area*bd120*rheati2 )
815  ;
816  EQU328..thhi2 =e= (1/3600)/2*(ratei2*Area*bd120*rheati2+ratei3*Area*bd120*rheati3 );
817  EQU329..thhi3 =e= (1/3600)/2*(ratei3*Area*bd120*rheati3+ratei4*Area*bd120*rheati4 );
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818  EQU330..thhi4 =e= (1/3600)/2*(ratei4*Area*bd120*rheati4+ratei5*Area*bd120*rheati5 );
819  EQU331..enthi2 =e= enthi1+h1*thhi1;
820  EQU332..enthi3 =e= enthi2+h1*thhi2;
821  EQU333..dti1 =e= 1/3600*ratei1*rheati1*BD120*(Pr**0.6667)/(av120*phio*Cpi1*tfi1/area*jhi1);
822  EQU334..enthi5 =e= enthi4+h1*thhi4;
823  EQU335..Mfi3 =e= 7934.4/area*(fiO23*32+fiSO23*64+f10n2*28+fiSO33*80 );
824  EQU336..enthi3 =e=  R*( fiO23*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasi3,ORD(J_H2) ) )- H298_O2+b1_O2 ) +
825    f10N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(Tgasi3,ORD(J_H2) ) )  - H298_N2 +b1_N2 ) +
826    fiSO23*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasi3,ORD(J_H2) ) )  - H298_SO2+b1_SO2 ) +
827    fiSO33* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasi3,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
828  EQU337..enthi4 =e=  R*( fiO24*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasi4,ORD(J_H2) ) )- H298_O2+b1_O2 ) +
829    f10N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(Tgasi4,ORD(J_H2) ) )  - H298_N2 +b1_N2 ) +
830    fiSO24*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasi4,ORD(J_H2) ) )  - H298_SO2+b1_SO2 ) +
831    fiSO34* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasi4,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
832  EQU338..enthi5 =e=  R*( fiO25*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(Tgasi5,ORD(J_H2) ) )- H298_O2+b1_O2 ) +
833    f10N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(Tgasi5,ORD(J_H2) ) )  - H298_N2 +b1_N2 ) +
834    fiSO25*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasi5,ORD(J_H2) ) )  - H298_SO2+b1_SO2 ) +
835    fiSO35* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasi5,ORD(J_H2) ) ) - H298_SO3 +b1_SO3 )  );
836  EQU339..Tgasi1 =e= T10;
837  EQU340..Tcati1=e= Tgasi1+dti1;
838  EQU341..Tcati2=e= Tgasi2+dti2;
839  EQU342..Tcati3=e= Tgasi3+dti3;
840  EQU343..enthi4 =e= enthi3+h1*thhi3;
841  EQU344..TriO22 =e= Tgasi2/ct_O2;
842  EQU345..Mfi1 =e= 7934.4/area*(fiO21*32+fiSO21*64+f10n2*28+fiSO31*80 );
843  EQU346..fiSO32 =e= fiSO31 - (fiSO22-fiSO21);
844  EQU347..fiO25 =e= fiO24+.5*(fiSO25-fiSO24);
845  EQU348..fiSO31=e= f10SO3;
846  EQU349..fiO24 =e= fiO23+.5*(fiSO24-fiSO23);
847  EQU350..fiO23 =e= fiO22+.5*(fiSO23-fiSO22);
848  EQU351..fiSO34 =e= fiSO33 - (fiSO24-fiSO23);
849  EQU352..TriO21 =e= Tgasi1/ct_O2;
850  EQU353..fiSO35 =e= fiSO34 - (fiSO25-fiSO24);
851  EQU354..TriO23 =e= Tgasi3/ct_O2;
852  EQU355..TriO24 =e= Tgasi4/ct_O2;
853  EQU356..TriO25 =e= Tgasi5/ct_O2;
854  EQU357..Trin21 =e= Tgasi1/ct_n2;
855  EQU358..Trin22 =e= Tgasi2/ct_n2;
856  EQU359..Trin23 =e= Tgasi3/ct_n2;
857  EQU360..enthi1 =e= h10;
858  EQU361..fiO22 =e= fiO21+.5*(fiSO22-fiSO21);
859  EQU362..Visci2 =e= ( Viscc_O2*FtriO22*fiO22+ Viscc_SO2*FtriSO22*fiSO22+ Viscc_SO3*FtriSO32*fiSO32
860                   + Viscc_n2*Ftrin22*f10n2 )/tfi2;
861  EQU363..Mfi4 =e= 7934.4/area*(fiO24*32+fiSO24*64+f10n2*28+fiSO34*80 );
862  EQU364..Mfi5 =e= 7934.4/area*(fiO25*32+fiSO25*64+f10n2*28+fiSO35*80 );
863  EQU365..jhi1=e= 0.91*(Mfi1/av120/phio/Visci1)**(-.51);
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864  EQU366..jhi2=e= 0.91*(Mfi2/av120/phio/Visci2)**(-.51);
865  EQU367..jhi3=e= 0.91*(Mfi3/av120/phio/Visci3)**(-.51);
866  EQU368..jhi4=e= 0.91*(Mfi4/av120/phio/Visci4)**(-.51);
867  EQU369..fiSO33 =e= fiSO32 - (fiSO23-fiSO22);
868  EQU370..Visci1 =e= ( Viscc_O2*FtriO21*fiO21+ Viscc_SO2*FtriSO21*fiSO21+ Viscc_SO3*FtriSO31*fiSO31
869                   + Viscc_n2*Ftrin21*f10n2 )/tfi1;
870  EQU371..Trin25 =e= Tgasi5/ct_n2;
871  EQU372..Visci3 =e= ( Viscc_O2*FtriO23*fiO23+ Viscc_SO2*FtriSO23*fiSO23+ Viscc_SO3*FtriSO33*fiSO33
872                   + Viscc_n2*Ftrin23*f10n2 )/tfi3;
873  EQU373..Visci4 =e= ( Viscc_O2*FtriO24*fiO24+ Viscc_SO2*FtriSO24*fiSO24+ Viscc_SO3*FtriSO34*fiSO34
874                   + Viscc_n2*Ftrin24*f10n2 )/tfi4;
875  EQU374..Visci5 =e= ( Viscc_O2*FtriO25*fiO25+ Viscc_SO2*FtriSO25*fiSO25+ Viscc_SO3*FtriSO35*fiSO35
876                   + Viscc_n2*Ftrin25*f10n2 )/tfi5;
877  EQU375..tfi1 =e= f10;
878  EQU376..fiSO35 =e= f11SO3;
879  EQU377..Kpi3   =e= 10**(5129/Tcati3-4.869);
880  EQU378..jhi5=e= 0.91*(Mfi5/av120/phio/Visci5)**(-.51);
881  EQU379..fiO25 =e= f11O2;
882  EQU380..Kpi4   =e= 10**(5129/Tcati4-4.869);
883  EQU381..enthi5 =e= H11;
884  EQU382..Tgasi5 =e= T11;
885  EQU383..fiSO25 =e= f11SO2;
886  EQU384..f11n2 =e= f10n2;
887  EQU385..f12SO2 =e= fiiSO21;
888  EQU386..f12O2 =e= fiiO21;
889  EQU387..f12 =e= tfii1;
890  EQU388..Kpi5   =e= 10**(5129/Tcati5-4.869);
891  EQU389..f12SO3 =e= fiiSO31;
892  EQU390..Tss2 =e= Tss1;
893  EQU391..Tsbd =e= Tss1;
894  EQU392..Hsbd =e= fsbd*factor2*( 1.0862*Tsbd - 5.6313e-4*Tsbd**2 +8.3449e-7*Tsbd**3 - 1.1427e4/Tsbd +1.0182e6/Tsbd**2   );
895  EQU393..fsbd =e= bdfrac * fss1;
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EQU394..fss1 =e= fss2 + fsbd;
EQU395..Pss2 =e= Psbd;
EQU396..f235o2=e=f24o2;
EQU397..f24 =e= f24o2 + f24n2 +f24so2 +f24so3;
EQU398..f235so2=e= f24so2;
EQU399..H24=E=R*(f24O2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(T24,ORD(J_H2)  )  ) - H298_O2+b1_O2) +
  f24N2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(T24,ORD(J_H2)   ) ) - H298_N2+b1_N2) +
  f24SO2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(T24,ORD(J_H2)  )  ) - H298_SO2+b1_SO2) +
  f24SO3*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)*POWER(T24,ORD(J_H2) ) )  - H298_SO3+b1_SO3) );
EQU400..Hsbfw =e= fsbfw*factor2*( 1.0862*Tsbfw - 5.6313e-4*Tsbfw**2 +8.3449e-7*Tsbfw**3 - 1.1427e4/Tsbfw +1.0182e6/Tsbfw**2
                                                                                         );
EQU401..f235so3=e= f24so3;
EQU402..fsbfw =e= fsw1;
EQU403..H24+Hsw1-H235-Hsbfw + ex71loss =E= 0;
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EQU404..f235n2=e=f24n2;
EQU405..H235-H24 - ex71loss -ex71area*ex71U*ex71dt=e=0;
EQU406..Ex71Dt =e= ( (T235- (Tsbfw-32)/1.8-273.1515) +  (T24- (Tsw1-32)/1.8-273.1515)  )/2.0;
EQU407..Hsw1 =e= fsw1*factor2*( 1.0862*Tsw1 - 5.6313e-4*Tsw1**2 +8.3449e-7*Tsw1**3 - 1.1427e4/Tsw1 +1.0182e6/Tsw1**2   );
EQU408..f25so2 =e= f24so2;
EQU409..f25n2 =e= f24n2;
EQU410..f25o2 =e= f24o2;
EQU411..F25 =e= f25o2+f25n2+f25so2;
EQU412..H08 =e= H07 * f08 / f07;
EQU413..f07O2 =e= f08O2 + f08aO2;
EQU414..f07N2 =e= f08N2 + f08aN2;
EQU415..f07SO2 =e= f08SO2 + f08aSO2;
EQU416..f07SO3 =e= f08SO3 + f08aSO3;
EQU417..H08a =e= H07 * f08a /f07;
EQU418..T07 =e= T08a;
EQU419..T07 =e= T08;
EQU420..f08 =e= f08O2+f08N2+f08SO2+f08SO3;
EQU421..f07n2 * bypass =e= f08an2;
EQU422..f08a =e= f08aO2+f08aN2+f08aSO2+f08aSO3;
EQU423..H14+H20-H13-H19 + ex66loss =E= 0;
EQU424..Ex66Dt =e= ( T13 - T20 + T14 - T19 )/2.0;
EQU425..H13-H14 - ex66area*ex66U*ex66dt=e=0;
EQU426..f14so2=e=f13so2;
EQU427..f14o2=e=f13o2;
EQU428..f20 =e= f20o2 +f20n2 + f20so2;
EQU429..f19 =e= f19o2 +f19n2 + f19so2;
EQU430..f14 =e= f14o2 +f14n2 + f14so2 + f14so3;
EQU431..H14 =E=R*( f14O2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(T14,ORD(J_H2) ) )  - H298_O2+b1_O2 ) +
  f14N2*  ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(T14,ORD(J_H2) ) )  - H298_N2+b1_N2 ) +
  f14SO2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T14,ORD(J_H2) ) ) - H298_SO2+b1_SO2 )  +
  f14SO3*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(T14,ORD(J_H2) ) ) - H298_SO3+b1_SO3 )  );
EQU432..f14n2=e=f13n2;
EQU433..f14so3=e=f13so3;
EQU434..H19 =E=  R*(f19O2*  ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(T19,ORD(J_H2)  )  )  - H298_O2+b1_O2 ) +
  f19N2*  ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(T19,ORD(J_H2)  ) )  - H298_N2+b1_N2 )  +
  f19SO2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T19,ORD(J_H2)  )  )  - H298_SO2+b1_SO2  )  );
EQU435..H20 =E=R*( f20O2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(T20,ORD(J_H2) ) )  - H298_O2+b1_O2 )  +
  f20N2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(T20,ORD(J_H2)  ) )  - H298_N2+b1_N2 )  +
  f20SO2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T20,ORD(J_H2)  )  )  - H298_SO2+b1_SO2  ) );
EQU436..f20o2=e=f19o2;
EQU437..f20n2=e=f19n2;
EQU438..f20so2=e= f19so2;
EQU439..f13 =e= f13o2 +f13n2 + f13so2 + f13so3;
EQU440..f16n2 =e= f15n2;
EQU441..f16o2 =e= f15o2;
EQU442..f16so2 =e= f15so2;
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EQU443..f10 =e= f10O2 + f10N2 + f10SO2 + f10SO3;
EQU444..H10 =e= R*( f10O2* (SUM(J_H2,1/ORD(J_H2)*Coe_H1("O2",J_H2)* POWER(T10, ORD(J_H2) ) ) - H298_O2+b1_O2) +
  f10N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(T10, ORD(J_H2) ) ) - H298_N2+b1_N2)  +
  f10SO2*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T10, ORD(J_H2) ) ) - H298_SO2+b1_SO2)  +
  f10SO3*(SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(T10, ORD(J_H2) ) ) - H298_SO3+b1_SO3)  );
EQU445..H10 =e= H08a + H09;
EQU446..f10SO3 =e= f08aSO3 + f09SO3;
EQU447..f10SO2  =e=  f08aSO2 + f09SO2;
EQU448..f10O2  =e= f08aO2 + f09O2;
EQU449..f10N2  =e= f08aN2 + f09N2;
EQU450..Hss1 =e= fss1*factor2*(1-bdfrac)*(5.3266*Tss1-0.2839*Pss1-7.3524e-3*Tss1**2+3.5815e-6*Tss1**3-7.2892e-5*Pss1**2+4.5954
        e-4*Tss1*Pss1)+fss1*factor2*bdfrac*(1.0862*Tss1-5.6313e-4*Tss1**2+8.3449e-7*Tss1**3-1.1427e4/Tss1+1.0182e6/Tss1**2);
EQU451..fss1 =e= fss1a + fss1b;
EQU452..f21 =e= f21o2 +f21n2 +f21so2 +f21so3;
EQU453..f22 =e= f22o2 + f22n2 + f22so2 + f22so3;
EQU454..f22n2=e=f21n2;
EQU455..f22so3=e= f21so3;
EQU456..f22o2=e=f21o2;
EQU457..HSHP1 =e= fSHP1* factor2*(  5.3266*TSHP1 - 0.2839*PSHP1 -7.3524e-3*TSHP1**2 + 3.5815e-6*TSHP1**3 -7.2892e-5*PSHP1**2
                                                                         + 4.5954e-4*TSHP1*PSHP1 );
EQU458..H22=E=R*(f22O2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(T22,ORD(J_H2)  )  ) - H298_O2+b1_O2) +
  f22N2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(T22,ORD(J_H2)   ) ) - H298_N2+b1_N2) +
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   f22SO2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(T22,ORD(J_H2)  )  ) - H298_SO2+b1_SO2) +
   f22SO3*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)*POWER(T22,ORD(J_H2) ) )  - H298_SO3+b1_SO3) );
EQU459..fss4=e=fsHP1;
EQU460..f22so2=e= f21so2;
EQU461..Ex67Dt =e= ( (T21- (Tss4-32)/1.8-273.1515) +  (T22- (TsHP1-32)/1.8-273.1515)  )/2.0;
EQU462..H21-H22 - ex67loss -ex67area*ex67U*ex67dt =e= 0;
EQU463..H22+HsHP1-H21-Hss4 + ex67loss =E= 0;
EQU464..H235=e= R*(f235O2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)*POWER(T235,ORD(J_H2)  )  ) - H298_O2+b1_O2) +
   f235N2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(T235,ORD(J_H2)   ) ) - H298_N2+b1_N2) +
   f235SO2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)*POWER(T235,ORD(J_H2)  )  ) - H298_SO2+b1_SO2) +
   f235SO3*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)*POWER(T235,ORD(J_H2) ) )  - H298_SO3+b1_SO3) );
EQU465..Ex68Dt =e= ( (T23- (Tss5-32)/1.8-273.1515) +  (T235- (TsHP2-32)/1.8-273.1515)  )/2.0;
EQU466..f235so3=e= f23so3;
EQU467..f235n2=e=f23n2;
EQU468..f235so2=e= f23so2;
EQU469..f235o2=e=f23o2;
EQU470..fss5=e=fsHP2;
EQU471..HSHP2 =e= fSHP2* factor2*(  5.3266*TSHP2 - 0.2839*PSHP2 -7.3524e-3*TSHP2**2 + 3.5815e-6*TSHP2**3
              -7.2892e-5*PSHP2**2 + 4.5954e-4*TSHP2*PSHP2 );
EQU472..H23-H235 - ex68loss -ex68area*ex68U*ex68dt=e=0;
EQU473..f235 =e= f235o2 + f235n2 + f235so2 + f235so3;
EQU474..f23 =e= f23o2 +f23n2 +f23so2 +f23so3;
EQU475..H235+HsHP2-H23-Hss5 + ex68loss =E= 0;
EQU476..Tss5 =e= Tss2;
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EQU477..Tss4 =e= Tss2;
EQU478..Pss5 =e= Pss2;
EQU479..Pss4 =e= Pss2;
EQU480..hss4 =e= hss2 * fss4 / fss2;
EQU481..hss5 =e= hss2 * fss5 / fss2;
EQU482..Tsw1b =e= Tsw1;
EQU483..Tsw1a =e= Tsw1;
EQU484..fsw1 =e= fsw1a + fsw1b;
EQU485..Hsw1b =e= fsw1b* hsw1 /fsw1;
EQU486..Hsw1a =e= fsw1a* hsw1 /fsw1;
EQU487..SO2ppm1 =e= f25SO2/f25 *1000;
EQU488..O2percent =e= f25O2 / f25 *100;
EQU489..f07so3 *bypass =e= f08aso3;
EQU490..tfiv1 =e= f22o2+f22n2+f22so2+f22so3;
EQU491..fivo21 =e= f22o2;
EQU492..fivso21 =e= f22so2;
EQU493..fivso31 =e= f22so3;
EQU494..ffivso21 =e= -(1.2583e-4)/2 *( rateiv2+rateiv1 )*Area*BD110;
EQU495..ffivso22 =e= -(1.2583e-4)/2 *( rateiv3+rateiv2 )*Area*BD110;
EQU496..ffivso23 =e= -(1.2583e-4)/2 *( rateiv4+rateiv3 )*Area*BD110;
EQU497..ffivso24 =e= -(1.2583e-4)/2 *( rateiv5+rateiv4 )*Area*BD110;
EQU498..fivso22 =e= fivso21+h4*ffivso21;
EQU499..fivso23 =e= fivso22+h4*ffivso22;
EQU500..fivso24 =e= fivso23+h4*ffivso23;
EQU501..fivso25 =e= fivso24+h4*ffivso24;
EQU502..tfiv2 =e= tfiv1 +.5*(fivso22-fivso21);
EQU503..tfiv3 =e= tfiv2 +.5*(fivso23-fivso22);
EQU504..tfiv4 =e= tfiv3 +.5*(fivso24-fivso23);
EQU505..tfiv5 =e= tfiv4 +.5*(fivso25-fivso24);
EQU506..tfiii1 =e= f20;
EQU507..H25 =E= R*( f25O2*  ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("O2",J_H2)* POWER(T25,ORD(J_H2)  )  )  - H298_O2+b1_O2) +
f25N2* ( SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)* POWER(T25,ORD(J_H2)  ) )  - H298_N2+b1_N2) +
  f25SO2*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(T25,ORD(J_H2)  )  ) - H298_SO2+b1_SO2) );
EQU508..f07o2*bypass =e= f08ao2;
EQU509..f07so2*bypass =e= f08aso2;
EQU510..bypass =e= f08a/f07;
EQU511..ffiiso21 =e= -(1.2583e-4)/2*( rateii2+rateii1)*Area*BD120;
EQU512..ffiiso22 =e= -(1.2583e-4)/2*( rateii3+rateii2)*Area*BD120;
EQU513..ffiiso23 =e= -(1.2583e-4)/2*( rateii4+rateii3)*Area*BD120;
EQU514..ffiiso24 =e= -(1.2583e-4)/2*( rateii5+rateii4)*Area*BD120;
EQU515..fiiso22 =e= fiiso21+h2*ffiiso21;
EQU516..fiiso23 =e= fiiso22+h2*ffiiso22;
EQU517..fiiso24 =e= fiiso23+h2*ffiiso23;
EQU518..fiiso25 =e= fiiso24+h2*ffiiso24;
EQU519..tfii2 =e= tfii1+.5*(fiiso22-fiiso21);
EQU520..tfii3 =e= tfii2+.5*(fiiso23-fiiso22);
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EQU521..tfii4 =e= tfii3+.5*(fiiso24-fiiso23);
EQU522..tfii5 =e= tfii4+.5*(fiiso25-fiiso24);
EQU523..fiio22 =e= fiio21+.5*(fiiso22-fiiso21);
EQU524..fiio23 =e= fiio22+.5*(fiiso23-fiiso22);
EQU525..fiio24 =e= fiio23+.5*(fiiso24-fiiso23);
EQU526..fiio25 =e= fiio24+.5*(fiiso25-fiiso24);
EQU527..fiiso32 =e= fiiso31 - (fiiso22-fiiso21);
EQU528..fiiso33 =e= fiiso32 - (fiiso23-fiiso22);
EQU529..fiiso34 =e= fiiso33 - (fiiso24-fiiso23);
EQU530..fiiso35 =e= fiiso34 - (fiiso25-fiiso24);
EQU531..enthii1=e= h12;
EQU532..rheatiii1 =e=(-1.055e-3)*1.827*( -24097-0.26*Tcatiii1 +(1.69e-3)*Tcatiii1**2+1.5e5/Tcatiii1 );
EQU533..rheatiii2 =e=(-1.055e-3)*1.827*( -24097-0.26*Tcatiii2 +(1.69e-3)*Tcatiii2**2+1.5e5/Tcatiii2 );
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EQU534..rheatiii3 =e=(-1.055e-3)*1.827*( -24097-0.26*Tcatiii3 +(1.69e-3)*Tcatiii3**2+1.5e5/Tcatiii3 );
EQU535..rheatiii4 =e=(-1.055e-3)*1.827*( -24097-0.26*Tcatiii4 +(1.69e-3)*Tcatiii4**2+1.5e5/Tcatiii4 );
EQU536..rheatiii5 =e=(-1.055e-3)*1.827*( -24097-0.26*Tcatiii5 +(1.69e-3)*Tcatiii5**2+1.5e5/Tcatiii5 );
EQU537..Cpiii1 =e=R/tfiii1*(fiiiO21*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasiii1, (ORD(J_Cp)-1) ) ) ) +
  f20N2* (   SUM(J_Cp,Coe_Cp("N2",J_Cp)*  POWER(Tgasiii1, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO21*(  SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiii1, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO31*( SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiii1, (ORD(J_Cp)-1) ) ) ) );
EQU538..Cpiii2 =e=R/tfiii2*(fiiiO22*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasiii2, (ORD(J_Cp)-1) ) ) ) +
  f20N2* (   SUM(J_Cp,Coe_Cp("N2",J_Cp)*  POWER(Tgasiii2, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO22*(  SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiii2, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO32*( SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiii2, (ORD(J_Cp)-1) ) ) ) );
EQU539..Cpiii3 =e=R/tfiii3*(fiiiO23*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasiii3, (ORD(J_Cp)-1) ) ) ) +
  f20N2* (   SUM(J_Cp,Coe_Cp("N2",J_Cp)*  POWER(Tgasiii3, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO23*(  SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiii3, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO33*( SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiii3, (ORD(J_Cp)-1) ) ) ) );
EQU540..Cpiii4 =e=R/tfiii4*(fiiiO24*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasiii4, (ORD(J_Cp)-1) ) ) ) +
  f20N2* (   SUM(J_Cp,Coe_Cp("N2",J_Cp)*  POWER(Tgasiii4, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO24*(  SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiii4, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO34*( SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiii4, (ORD(J_Cp)-1) ) ) ) );
EQU541..Cpiii5 =e=R/tfiii5*(fiiiO25*( SUM(J_Cp,Coe_Cp("O2",J_Cp)*POWER(Tgasiii5, (ORD(J_Cp)-1) ) ) ) +
  f20N2* (   SUM(J_Cp,Coe_Cp("N2",J_Cp)*  POWER(Tgasiii5, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO25*(  SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiii5, (ORD(J_Cp)-1) ) ) ) +
  fiiiSO35*( SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiii5, (ORD(J_Cp)-1) ) ) ) );
EQU542..Mfiii1 =e= 7934.4/area*( fiiio21*32+fiiiso21*64+f06n2*28+fiiiso31*80 );
EQU543..Mfiii2 =e= 7934.4/area*( fiiio22*32+fiiiso22*64+f06n2*28+fiiiso32*80 );
EQU544..Mfiii3 =e= 7934.4/area*( fiiio23*32+fiiiso23*64+f06n2*28+fiiiso33*80 );
EQU545..Mfiii4 =e= 7934.4/area*( fiiio24*32+fiiiso24*64+f06n2*28+fiiiso34*80 );
EQU546..Mfiii5 =e= 7934.4/area*( fiiio25*32+fiiiso25*64+f06n2*28+fiiiso35*80 );
EQU547..jhiii1 =e=  0.91*(Mfiii1/av110/phio/Visciii1)**(-.51);
EQU548..jhiii2 =e=  0.91*(Mfiii2/av110/phio/Visciii2)**(-.51);
EQU549..jhiii3 =e=  0.91*(Mfiii3/av110/phio/Visciii3)**(-.51);
EQU550..jhiii4 =e=  0.91*(Mfiii4/av110/phio/Visciii4)**(-.51);
 EQU551..jhiii5 =e=  0.91*(Mfiii5/av110/phio/Visciii5)**(-.51);

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EQU552..Visciii1 =e= ( Viscc_o2*Ftriiio21*fiiio21+ Viscc_so2*Ftriiiso21*fiiiso21+ Viscc_so3*Ftriiiso31*fiiiso31
                + Viscc_n2*Ftriiin21*f06n2 )/tfiii1;
EQU553..Visciii2 =e= ( Viscc_o2*Ftriiio22*fiiio22+ Viscc_so2*Ftriiiso22*fiiiso22+ Viscc_so3*Ftriiiso32*fiiiso32
                + Viscc_n2*Ftriiin22*f06n2 )/tfiii2;
EQU554..Visciii3 =e= ( Viscc_o2*Ftriiio23*fiiio23+ Viscc_so2*Ftriiiso23*fiiiso23+ Viscc_so3*Ftriiiso33*fiiiso33
                + Viscc_n2*Ftriiin23*f06n2 )/tfiii3;

EQU555..Visciii4 =e= ( Viscc_o2*Ftriiio24*fiiio24+ Viscc_so2*Ftriiiso24*fiiiso24+ Viscc_so3*Ftriiiso34*fiiiso34
                + Viscc_n2*Ftriiin24*f06n2 )/tfiii4;
EQU556..Visciii5 =e= ( Viscc_o2*Ftriiio25*fiiio25+ Viscc_so2*Ftriiiso25*fiiiso25+ Viscc_so3*Ftriiiso35*fiiiso35
                + Viscc_n2*Ftriiin25*f06n2 )/tfiii5;
EQU557..Triiio21 =e= Tgasiii1/ct_o2;
EQU558..Triiio22 =e= Tgasiii2/ct_o2;
EQU559..Triiio23 =e= Tgasiii3/ct_o2;
EQU560..Triiio24 =e= Tgasiii4/ct_o2;
EQU561..Triiio25 =e= Tgasiii5/ct_o2;
EQU562..Triiin21 =e= Tgasiii1/ct_n2;
EQU563..Triiin22 =e= Tgasiii2/ct_n2;
EQU564..Triiin23 =e= Tgasiii3/ct_n2;
EQU565..Triiin24 =e= Tgasiii4/ct_n2;
EQU566..Triiin25 =e= Tgasiii5/ct_n2;
EQU567..Triiiso21 =e= Tgasiii1/ct_so2;
EQU568..Triiiso22 =e= Tgasiii2/ct_so2;
EQU569..Triiiso23 =e= Tgasiii3/ct_so2;
EQU570..Triiiso24 =e= Tgasiii4/ct_so2;
EQU571..Triiiso25 =e= Tgasiii5/ct_so2;
EQU572..Triiiso31 =e= Tgasiii1/ct_so3;
EQU573..Triiiso32 =e= Tgasiii2/ct_so3;
EQU574..Triiiso33 =e= Tgasiii3/ct_so3;
EQU575..Triiiso34 =e= Tgasiii4/ct_so3;
EQU576..Triiiso35 =e= Tgasiii5/ct_so3;
EQU577..Ftriiio21=e=1.058*Triiio21**.645 - .261/((1.9* Triiio21)**(.9*log10(1.9*Triiio21)) );
EQU578..Ftriiio22=e=1.058*Triiio22**.645 - .261/((1.9* Triiio22)**(.9*log10(1.9*Triiio22)) );
EQU579..Ftriiio23=e=1.058*Triiio23**.645 - .261/((1.9* Triiio23)**(.9*log10(1.9*Triiio23)) );
EQU580..Ftriiio24=e=1.058*Triiio24**.645 - .261/((1.9* Triiio24)**(.9*log10(1.9*Triiio24)) );
EQU581..Ftriiio25=e=1.058*Triiio25**.645 - .261/((1.9* Triiio25)**(.9*log10(1.9*Triiio25)) );
EQU582..Ftriiin21=e=1.058*Triiin21**.645 - .261/((1.9* Triiin21)**(.9*log10(1.9*Triiin21)) );
EQU583..Ftriiin22=e=1.058*Triiin22**.645 - .261/((1.9* Triiin22)**(.9*log10(1.9*Triiin22)) );
EQU584..Ftriiin23=e=1.058*Triiin23**.645 - .261/((1.9* Triiin23)**(.9*log10(1.9*Triiin23)) );
EQU585..Ftriiin24=e=1.058*Triiin24**.645 - .261/((1.9* Triiin24)**(.9*log10(1.9*Triiin24)) );
EQU586..Ftriiin25=e=1.058*Triiin25**.645 - .261/((1.9* Triiin25)**(.9*log10(1.9*Triiin25)) );
EQU587..Ftriiiso21=e=1.058*Triiiso21**.645 - .261/((1.9* Triiiso21)**(.9*log10(1.9*Triiiso21)) );
EQU588..Ftriiiso22=e=1.058*Triiiso22**.645 - .261/((1.9* Triiiso22)**(.9*log10(1.9*Triiiso22)) );
EQU589..Ftriiiso23=e=1.058*Triiiso23**.645 - .261/((1.9* Triiiso23)**(.9*log10(1.9*Triiiso23)) );
EQU590..Ftriiiso24=e=1.058*Triiiso24**.645 - .261/((1.9* Triiiso24)**(.9*log10(1.9*Triiiso24)) );
EQU591..Ftriiiso25=e=1.058*Triiiso25**.645 - .261/((1.9* Triiiso25)**(.9*log10(1.9*Triiiso25)) );
 EQU592..Ftriiiso31=e=1.058*Triiiso31**.645 - .261/((1.9* Triiiso31)**(.9*log10(1.9*Triiiso31)) );
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EQU593..Ftriiiso32=e=1.058*Triiiso32**.645 - .261/((1.9* Triiiso32)**(.9*log10(1.9*Triiiso32)) );
EQU594..Ftriiiso33=e=1.058*Triiiso33**.645 - .261/((1.9* Triiiso33)**(.9*log10(1.9*Triiiso33)) );
EQU595..Ftriiiso34=e=1.058*Triiiso34**.645 - .261/((1.9* Triiiso34)**(.9*log10(1.9*Triiiso34)) );
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1140  EQU596..Ftriiiso35=e=1.058*Triiiso35**.645 - .261/((1.9* Triiiso35)**(.9*log10(1.9*Triiiso35)) );
1141  EQU597..rateiii1 =e= rateiniii1*effiii;
1142  EQU598..rateiii2 =e= rateiniii2*effiii;
1143  EQU599..rateiii3 =e= rateiniii3*effiii;
1144  EQU600..rateiii4 =e= rateiniii4*effiii;
1145  EQU601..rateiii5 =e= rateiniii5*effiii;
1146  EQU602..rateiniii1 =e=( ((pres("iii","1")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiii1101 +ciii1101*
1147                 ( f10so2/f10*pres("iii","1") ) +diii1101*(pres("iii","1")*fiiiso31/tfiii1) )**2
1148                *( 1-fiiiso31/( kpiii1*fiiiso21*(pres("iii","1")*fiiio21/tfiii1)**.5 ) );
1149  EQU603..rateiniii2 =e=( ((pres("iii","2")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiii1102 +ciii1102*
1150                 ( f10so2/f10*pres("iii","2") ) +diii1102*(pres("iii","2")*fiiiso32/tfiii2) )**2
1151                *( 1-fiiiso32/( kpiii2*fiiiso22*(pres("iii","2")*fiiio22/tfiii2)**.5 ) );
1152  EQU604..rateiniii3 =e=( ((pres("iii","3")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiii1103 +ciii1103*
1153                 ( f10so2/f10*pres("iii","3") ) +diii1101*(pres("iii","3")*fiiiso33/tfiii3) )**2
1154                *( 1-fiiiso33/( kpiii3*fiiiso23*(pres("iii","3")*fiiio23/tfiii3)**.5 ) );
1155  EQU605..rateiniii4 =e=( ((pres("iii","4")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiii1104 +ciii1104*
1156                 ( f10so2/f10*pres("iii","4") ) +diii1104*(pres("iii","4")*fiiiso34/tfiii4) )**2
1157                *( 1-fiiiso34/( kpiii4*fiiiso24*(pres("iii","4")*fiiio24/tfiii4)**.5 ) );
1158  EQU606..rateiniii5 =e=( ((pres("iii","5")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiii1105 +ciii1105*
1159                 ( f10so2/f10*pres("iii","5") ) +diii1105*(pres("iii","5")*fiiiso35/tfiii5) )**2
1160                *( 1-fiiiso35/( kpiii5*fiiiso25*(pres("iii","5")*fiiio25/tfiii5)**.5 ) );
1161  EQU607..aiii1101 =e= exp(-6.80+4960/Tcatiii1);
1162  EQU608..aiii1102 =e= exp(-6.80+4960/Tcatiii2);
1163  EQU609..aiii1103 =e= exp(-6.80+4960/Tcatiii3);
1164  EQU610..aiii1104 =e= exp(-6.80+4960/Tcatiii4);
1165  EQU611..aiii1105 =e= exp(-6.80+4960/Tcatiii5);
1166  EQU612..ciii1101=e= exp(10.32-7350/Tcatiii1);
1167  EQU613..ciii1102=e= exp(10.32-7350/Tcatiii2);
1168  EQU614..ciii1103=e= exp(10.32-7350/Tcatiii3);
1169  EQU615..ciii1104=e= exp(10.32-7350/Tcatiii4);
1170  EQU616..ciii1105=e= exp(10.32-7350/Tcatiii5);
1171  EQU617..diii1101 =e= exp(-7.58+6370/Tcatiii1);
1172  EQU618..diii1102 =e= exp(-7.58+6370/Tcatiii2);
1173  EQU619..diii1103 =e= exp(-7.58+6370/Tcatiii3);
1174  EQU620..diii1104 =e= exp(-7.58+6370/Tcatiii4);
1175  EQU621..diii1105 =e= exp(-7.58+6370/Tcatiii5);
1176  EQU622..Kpiii1 =e= 10**(5129/Tcatiii1-4.869);
1177  EQU623..Kpiii2 =e= 10**(5129/Tcatiii2-4.869);
1178  EQU624..Kpiii3 =e= 10**(5129/Tcatiii3-4.869);
1179  EQU625..Kpiii4 =e= 10**(5129/Tcatiii4-4.869);
1180  EQU626..Kpiii5 =e= 10**(5129/Tcatiii5-4.869);
1181  EQU627..fiiio25 =e= f21o2;
1182  EQU628..fiiiso25 =e= f21so2;
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1183  EQU629..fiiiso35 =e= f21so3;
1184  EQU630..Tgasiii5 =e= T21;
1185  EQU631..enthiii5 =e= H21;
1186  EQU632..f20n2 =e= f21n2;
1187  EQU633..fivo22 =e= fivo21+.5*(fivso22-fivso21);
1188  EQU634..fivo23 =e= fivo22+.5*(fivso23-fivso22);
1189  EQU635..fivo24 =e= fivo23+.5*(fivso24-fivso23);
1190  EQU636..fivo25 =e= fivo24+.5*(fivso25-fivso24);
1191  EQU637..fivso32 =e= fivso31-(fivso22-fivso21);
1192  EQU638..fivso33 =e= fivso32-(fivso23-fivso22);
1193  EQU639..fivso34 =e= fivso33-(fivso24-fivso23);
1194  EQU640..fivso35 =e= fivso34-(fivso25-fivso24);
1195  EQU641..enthiv1 =e= h22;
1196  EQU642..thhiv1 =e=(1/3600/2)* (  rateiv1*Area*bd110*rheativ1+rateiv2*Area*bd110*rheativ2 );
1197  EQU643..thhiv2 =e=(1/3600/2)* (  rateiv2*Area*bd110*rheativ2+rateiv3*Area*bd110*rheativ3 );
1198  EQU644..thhiv3 =e=(1/3600/2)* (  rateiv3*Area*bd110*rheativ3+rateiv4*Area*bd110*rheativ4 );
1199  EQU645..thhiv4 =e=(1/3600/2)* (  rateiv4*Area*bd110*rheativ4+rateiv5*Area*bd110*rheativ5 );
1200  EQU646..enthiv2 =e= enthiv1+h4*thhiv1;
1201  EQU647..enthiv3 =e= enthiv2+h4*thhiv2;
1202  EQU648..enthiv4 =e= enthiv3+h4*thhiv3;
1203  EQU649..enthiv5 =e= enthiv4+h4*thhiv4;
1204  EQU650..enthiv2=e=R*(fivO22*(SUM(J_H2,1/ORD(J_H2)*Coe_H1("O2",J_H2)*POWER(Tgasiv2,ORD(J_H2)))-H298_O2+b1_O2) +
1205     f22N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiv2,ORD(J_H2)   ) )  - H298_N2+b1_N2) +
1206     fivSO22*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasiv2,ORD(J_H2) ) )-H298_SO2+b1_SO2) +
1207     fivSO32* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiv2,ORD(J_H2)   ) ) - H298_SO3 +b1_SO3));
1208  EQU651..enthiv3=e=R*(fivO23*(SUM(J_H2,1/ORD(J_H2)*Coe_H1("O2",J_H2)*POWER(Tgasiv3,ORD(J_H2)))-H298_O2+b1_O2) +
1209     f22N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiv3,ORD(J_H2)   ) )  - H298_N2+b1_N2) +
1210     fivSO23*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasiv3,ORD(J_H2) ) )-H298_SO2+b1_SO2) +
1211     fivSO33* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiv3,ORD(J_H2)   ) ) - H298_SO3 +b1_SO3));
1212  EQU652..enthiv4=e=R*(fivO24*(SUM(J_H2,1/ORD(J_H2)*Coe_H1("O2",J_H2)*POWER(Tgasiv4,ORD(J_H2)))-H298_O2+b1_O2) +
1213     f22N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiv4,ORD(J_H2)   ) )  - H298_N2+b1_N2) +
1214     fivSO24*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasiv4,ORD(J_H2) ) )-H298_SO2+b1_SO2) +
1215     fivSO34* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiv4,ORD(J_H2)   ) ) - H298_SO3 +b1_SO3));
1216  EQU653..enthiv5=e=R*(fivO25*(SUM(J_H2,1/ORD(J_H2)*Coe_H1("O2",J_H2)*POWER(Tgasiv5,ORD(J_H2)))-H298_O2+b1_O2) +
1217     f22N2* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("N2",J_H2)*POWER(Tgasiv5,ORD(J_H2)   ) )  - H298_N2+b1_N2) +
1218     fivSO25*( SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO2",J_H2)* POWER(Tgasiv5,ORD(J_H2) ) )-H298_SO2+b1_SO2) +
1219     fivSO35* (SUM(J_H2,1/ORD(J_H2) *Coe_H1("SO3",J_H2)* POWER(Tgasiv5,ORD(J_H2)   ) ) - H298_SO3 +b1_SO3));
1220  EQU654..Tgasiv1 =e= T22;
1221  EQU655..Tcativ1 =e= Tgasiv1+dtiv1;
1222  EQU656..Tcativ2 =e= Tgasiv2+dtiv2;
1223  EQU657..Tcativ3 =e= Tgasiv3+dtiv3;
1224  EQU658..Tcativ4 =e= Tgasiv4+dtiv4;
1225  EQU659..Tcativ5 =e= Tgasiv5+dtiv5;
1226  EQU660..dtiv1=e=1/3600*rateiv1*rheativ1*BD110*(Pr**0.6667) /(av110*phio*Cpiv1*tfiv1/area*jhiv1);
1227  EQU661..dtiv2=e=1/3600*rateiv2*rheativ2*BD110*(Pr**0.6667) /(av110*phio*Cpiv2*tfiv2/area*jhiv2);
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1228  EQU662..dtiv3=e=1/3600*rateiv3*rheativ3*BD110*(Pr**0.6667) /(av110*phio*Cpiv3*tfiv3/area*jhiv3);

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1229  EQU663..dtiv4=e=1/3600*rateiv4*rheativ4*BD110*(Pr**0.6667) /(av110*phio*Cpiv4*tfiv4/area*jhiv4);
1230  EQU664..dtiv5=e=1/3600*rateiv5*rheativ5*BD110*(Pr**0.6667) /(av110*phio*Cpiv5*tfiv5/area*jhiv5);
1231  EQU665..rheativ1 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcativ1+(1.69e-3)*Tcativ1**2+1.5e5/Tcativ1 );
1232  EQU666..rheativ2 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcativ2+(1.69e-3)*Tcativ2**2+1.5e5/Tcativ2 );
1233  EQU667..rheativ3 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcativ3+(1.69e-3)*Tcativ3**2+1.5e5/Tcativ3 );
1234  EQU668..rheativ4 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcativ4+(1.69e-3)*Tcativ4**2+1.5e5/Tcativ4 );
1235  EQU669..rheativ5 =e= (-1.055e-3)*1.827*( -24097-0.26*Tcativ5+(1.69e-3)*Tcativ5**2+1.5e5/Tcativ5 );
1236  EQU670..Cpiv1 =e= R/tfiv1*( fivO21*(SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasiv1, (ORD(J_Cp)-1) ) ) )  +
1237    f22N2* (      SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasiv1, (ORD(J_Cp)-1) ) ) ) +
1238    fivSO21*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiv1, (ORD(J_Cp)-1) ) ) )  +
1239    fivSO31*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiv1, (ORD(J_Cp)-1) ) ) )  );
1240  EQU671..Cpiv2 =e= R/tfiv2*( fivO22*(SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasiv2, (ORD(J_Cp)-1) ) ) )  +
1241    f22N2* (      SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasiv2, (ORD(J_Cp)-1) ) ) ) +
1242    fivSO22*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiv2, (ORD(J_Cp)-1) ) ) )  +
1243    fivSO32*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiv2, (ORD(J_Cp)-1) ) ) )  );
1244  EQU672..Cpiv3 =e= R/tfiv3*( fivO23*(SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasiv3, (ORD(J_Cp)-1) ) ) )  +
1245    f22N2* (      SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasiv3, (ORD(J_Cp)-1) ) ) ) +
1246    fivSO23*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiv3, (ORD(J_Cp)-1) ) ) )  +
1247    fivSO33*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiv3, (ORD(J_Cp)-1) ) ) )  );
1248  EQU673..Cpiv4 =e= R/tfiv4*( fivO24*(SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasiv4, (ORD(J_Cp)-1) ) ) )  +
1249    f22N2* (      SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasiv4, (ORD(J_Cp)-1) ) ) ) +
1250    fivSO24*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiv4, (ORD(J_Cp)-1) ) ) )  +
1251    fivSO34*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiv4, (ORD(J_Cp)-1) ) ) )  );
1252  EQU674..Cpiv5 =e= R/tfiv5*( fivO25*(SUM(J_Cp,Coe_Cp("O2",J_Cp)* POWER(Tgasiv5, (ORD(J_Cp)-1) ) ) )  +
1253    f22N2* (      SUM(J_Cp,Coe_Cp("N2",J_Cp)* POWER(Tgasiv5, (ORD(J_Cp)-1) ) ) ) +
1254    fivSO25*(SUM(J_Cp,Coe_Cp("SO2",J_Cp)*  POWER(Tgasiv5, (ORD(J_Cp)-1) ) ) )  +
1255    fivSO35*(SUM(J_Cp,Coe_Cp("SO3",J_Cp)*  POWER(Tgasiv5, (ORD(J_Cp)-1) ) ) )  );
1256  EQU675..Mfiv1 =e= 7934.4/area*(fivo21*32+ fivso21*64+f06n2*28+fivso31*80 );
1257  EQU676..Mfiv2 =e= 7934.4/area*(fivo22*32+ fivso22*64+f06n2*28+fivso32*80 );
1258  EQU677..Mfiv3 =e= 7934.4/area*(fivo23*32+ fivso23*64+f06n2*28+fivso33*80 );
1259  EQU678..Mfiv4 =e= 7934.4/area*(fivo24*32+ fivso24*64+f06n2*28+fivso34*80 );
1260  EQU679..Mfiv5 =e= 7934.4/area*(fivo25*32+ fivso25*64+f06n2*28+fivso35*80 );
1261  EQU680..jhiv1 =e= 0.91*(Mfiv1/av110/phio/Visciv1)**(-.51);
1262  EQU681..jhiv2 =e= 0.91*(Mfiv2/av110/phio/Visciv2)**(-.51);
1263  EQU682..jhiv3 =e= 0.91*(Mfiv3/av110/phio/Visciv3)**(-.51);
1264  EQU683..Visciv1 =e= ( Viscc_o2*Ftrivo21*fivo21+ Viscc_so2*Ftrivso21*fivso21+ Viscc_so3*Ftrivso31*fivso31+ Viscc_n2*Ftrivn21*f0
                                                                                   6n2 )/tfiv1;
1265  EQU684..jhiv4 =e= 0.91*(Mfiv4/av110/phio/Visciv4)**(-.51);
1266  EQU685..jhiv5 =e= 0.91*(Mfiv5/av110/phio/Visciv5)**(-.51);
1267  EQU686..Visciv2 =e= ( Viscc_o2*Ftrivo22*fivo22+ Viscc_so2*Ftrivso22*fivso22+ Viscc_so3*Ftrivso32*fivso32+ Viscc_n2*Ftrivn22*f0
                                                                                   6n2 )/tfiv2;
1268  EQU687..Visciv3 =e= ( Viscc_o2*Ftrivo23*fivo23+ Viscc_so2*Ftrivso23*fivso23+ Viscc_so3*Ftrivso33*fivso33+ Viscc_n2*Ftrivn23*f0
                                                                                   6n2 )/tfiv3;
1269  EQU688..Visciv4 =e= ( Viscc_o2*Ftrivo24*fivo24+ Viscc_so2*Ftrivso24*fivso24+ Viscc_so3*Ftrivso34*fivso34+ Viscc_n2*Ftrivn24*f0
                                                                                   6n2 )/tfiv4;
1270  EQU689..Visciv5 =e= ( Viscc_o2*Ftrivo25*fivo25+ Viscc_so2*Ftrivso25*fivso25+ Viscc_so3*Ftrivso35*fivso35+ Viscc_n2*Ftrivn25*f0
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                                                                                   6n2 )/tfiv5;
1271  EQU690..Trivo21 =e= Tgasiv1/ct_o2;
1272  EQU691..Trivo22 =e= Tgasiv2/ct_o2;
1273  EQU692..Trivo23 =e= Tgasiv3/ct_o2;
1274  EQU693..Trivo24 =e= Tgasiv4/ct_o2;
1275  EQU694..Trivo25 =e= Tgasiv5/ct_o2;
1276  EQU695..Trivn21 =e= Tgasiv1/ct_n2;
1277  EQU696..Trivn22 =e= Tgasiv2/ct_n2;
1278  EQU697..Trivn23 =e= Tgasiv3/ct_n2;
1279  EQU698..Trivn24 =e= Tgasiv4/ct_n2;
1280  EQU699..Trivn25 =e= Tgasiv5/ct_n2;
1281  EQU700..Trivso21 =e= Tgasiv1/ct_so2;
1282  EQU701..Trivso22 =e= Tgasiv2/ct_so2;
1283  EQU702..Trivso23 =e= Tgasiv3/ct_so2;
1284  EQU703..Trivso24 =e= Tgasiv4/ct_so2;
1285  EQU704..Trivso25 =e= Tgasiv5/ct_so2;
1286  EQU705..Trivso31 =e= Tgasiv1/ct_so3;
1287  EQU706..Trivso32 =e= Tgasiv2/ct_so3;
1288  EQU707..Trivso33 =e= Tgasiv3/ct_so3;
1289  EQU708..Trivso34 =e= Tgasiv4/ct_so3;
1290  EQU709..Trivso35 =e= Tgasiv5/ct_so3;
1291  EQU710..Ftrivo21=e=1.058*Trivo21**.645 - .261/( (1.9* Trivo21)**(.9*log10(1.9*Trivo21)) );
1292  EQU711..Ftrivo22=e=1.058*Trivo22**.645 - .261/( (1.9* Trivo22)**(.9*log10(1.9*Trivo22)) );
1293  EQU712..Ftrivo23=e=1.058*Trivo23**.645 - .261/( (1.9* Trivo23)**(.9*log10(1.9*Trivo23)) );
1294  EQU713..Ftrivo24=e=1.058*Trivo24**.645 - .261/( (1.9* Trivo24)**(.9*log10(1.9*Trivo24)) );
1295  EQU714..Ftrivo25=e=1.058*Trivo25**.645 - .261/( (1.9* Trivo25)**(.9*log10(1.9*Trivo25)) );
1296  EQU715..Ftrivn21=e=1.058*Trivn21**.645 - .261/( (1.9* Trivn21)**(.9*log10(1.9*Trivn21)) );
1297  EQU716..Ftrivn22=e=1.058*Trivn22**.645 - .261/( (1.9* Trivn22)**(.9*log10(1.9*Trivn22)) );
1298  EQU717..Ftrivn23=e=1.058*Trivn23**.645 - .261/( (1.9* Trivn23)**(.9*log10(1.9*Trivn23)) );
1299  EQU718..Ftrivn24=e=1.058*Trivn24**.645 - .261/( (1.9* Trivn24)**(.9*log10(1.9*Trivn24)) );
1300  EQU719..Ftrivn25=e=1.058*Trivn25**.645 - .261/( (1.9* Trivn25)**(.9*log10(1.9*Trivn25)) );
1301  EQU720..Ftrivso21=e=1.058*Trivso21**.645 - .261/( (1.9* Trivso21)**(.9*log10(1.9*Trivso21)) );
1302  EQU721..Ftrivso22=e=1.058*Trivso22**.645 - .261/( (1.9* Trivso22)**(.9*log10(1.9*Trivso22)) );
1303  EQU722..Ftrivso23=e=1.058*Trivso23**.645 - .261/( (1.9* Trivso23)**(.9*log10(1.9*Trivso23)) );
1304  EQU723..Ftrivso24=e=1.058*Trivso24**.645 - .261/( (1.9* Trivso24)**(.9*log10(1.9*Trivso24)) );
1305  EQU724..Ftrivso25=e=1.058*Trivso25**.645 - .261/( (1.9* Trivso25)**(.9*log10(1.9*Trivso25)) );
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EQU725..Ftrivso31=e=1.058*Trivso31**.645 - .261/( (1.9* Trivso31)**(.9*log10(1.9*Trivso31)) );
EQU726..Ftrivso32=e=1.058*Trivso32**.645 - .261/( (1.9* Trivso32)**(.9*log10(1.9*Trivso32)) );
EQU727..Ftrivso33=e=1.058*Trivso33**.645 - .261/( (1.9* Trivso33)**(.9*log10(1.9*Trivso33)) );
EQU728..Ftrivso34=e=1.058*Trivso34**.645 - .261/( (1.9* Trivso34)**(.9*log10(1.9*Trivso34)) );
EQU729..Ftrivso35=e=1.058*Trivso35**.645 - .261/( (1.9* Trivso35)**(.9*log10(1.9*Trivso35)) );
EQU730..rateiv1 =e= rateintiv1*effiv;
EQU731..rateiv2 =e= rateintiv2*effiv;
EQU732..rateiv3 =e= rateintiv3*effiv;
EQU733..rateiv4 =e= rateintiv4*effiv;
EQU734..rateiv5 =e= rateintiv5*effiv;
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EQU735..rateintiv1 =e= ( ((pres("iv","1")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiv1101+civ1101* ( f10so2/f10*pres("iv","1") )
                                                                                               +div1101*
             (pres("iv","1")*fivso31/tfiv1) )**2*( 1-fivso31/( kpiv1*fivso21* (pres("iv","1")*fivo21/tfiv1)**.5 ) );
EQU736..rateintiv2 =e= ( ((pres("iv","2")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiv1102+civ1102* ( f10so2/f10*pres("iv","2") )
                                                                                               +div1102*
             (pres("iv","2")*fivso32/tfiv2) )**2*( 1-fivso32/( kpiv2*fivso22* (pres("iv","2")*fivo22/tfiv2)**.5 ) );
EQU737..rateintiv3 =e= ( ((pres("iv","3")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiv1103+civ1103* ( f10so2/f10*pres("iv","3") )
                                                                                               +div1103*
             (pres("iv","3")*fivso33/tfiv3) )**2*( 1-fivso33/( kpiv3*fivso23* (pres("iv","3")*fivo23/tfiv3)**.5 ) );
EQU738..rateintiv4 =e= ( ((pres("iv","4")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiv1104+civ1104* ( f10so2/f10*pres("iv","4") )
                                                                                               +div1104*
             (pres("iv","4")*fivso34/tfiv4) )**2*( 1-fivso34/( kpiv4*fivso24* (pres("iv","4")*fivo24/tfiv4)**.5 ) );
EQU739..rateintiv5 =e= ( ((pres("iv","5")/f10)**1.5) *f10so2*(f10o2**.5) ) /( Aiv1105+civ1105* ( f10so2/f10*pres("iv","5") )
                                                                                               +div1105*
             (pres("iv","5")*fivso35/tfiv5) )**2*( 1-fivso35/( kpiv5*fivso25* (pres("iv","5")*fivo25/tfiv5)**.5 ) );
EQU740..aiv1101 =e= exp(-6.80+4960/Tcativ1);
EQU741..aiv1102 =e= exp(-6.80+4960/Tcativ2);
EQU742..aiv1103 =e= exp(-6.80+4960/Tcativ3);
EQU743..aiv1104 =e= exp(-6.80+4960/Tcativ4);
EQU744..aiv1105 =e= exp(-6.80+4960/Tcativ5);
EQU745..civ1101 =e= exp(10.32-7350/Tcativ1);
EQU746..civ1102 =e= exp(10.32-7350/Tcativ2);
EQU747..civ1103 =e= exp(10.32-7350/Tcativ3);
EQU748..civ1104 =e= exp(10.32-7350/Tcativ4);
EQU749..civ1105 =e= exp(10.32-7350/Tcativ5);
EQU750..div1101 =e= exp(-7.58+6370/Tcativ1);
EQU751..div1102 =e= exp(-7.58+6370/Tcativ2);
EQU752..div1103 =e= exp(-7.58+6370/Tcativ3);
EQU753..div1104 =e= exp(-7.58+6370/Tcativ4);
EQU754..div1105 =e= exp(-7.58+6370/Tcativ5);
EQU755..Kpiv1   =e= 10**(5129/Tcativ1-4.869);
EQU756..Kpiv2   =e= 10**(5129/Tcativ2-4.869);
EQU757..Kpiv3   =e= 10**(5129/Tcativ3-4.869);
EQU758..Kpiv4   =e= 10**(5129/Tcativ4-4.869);
EQU759..Kpiv5   =e= 10**(5129/Tcativ5-4.869);
EQU760..f22n2 =e= f23n2;
EQU761..fivo25 =e= f23o2;
EQU762..fivso25 =e= f23so2;
EQU763..fivso35 =e= f23so3;
EQU764..Tgasiv5 =e= T23;
EQU765..enthiv5 =e= H23;

F06.L=1.741; f50.L=0.245; fsbfw.L=1.93;
O2percent.L=6; Pshp1.L=614.7; Pshp2.L=614.7;
Pss2.L=709.7; SO2ppm.L=355; T06.L=359.8166667;
T07.L=1321.483333; T09.L=646.4833333; T10.L=708;

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T11.L=893.7055556; T12.L=689.2611111; T13.L=785.9277778;
T15.L=501.4833333; T16.L=349.8166667; T19.L=549.2611111;
T20.L=690.9277778; T21.L=737.0388889; T22.L=683.4532;
T23.L=692.5944444; T235.L=673.15; T24.L=504.8166667;
T25.L=350.3722222; Tsbfw.L=225; TSHP1.L=665;
TSHP2.L=650; TSW1.L=340;
F06.LO=1.7; f50.LO=0.22; fsbfw.LO=1.91;
O2percent.LO=5; Pshp1.LO=550; Pshp2.LO=550;
Pss2.LO=700; SO2ppm.LO=100; T06.LO=355;
T07.LO=1315; T09.LO=640; T10.LO=690;
T11.LO=890; T12.LO=685; T13.LO=780;
T15.LO=495; T16.LO=345; T19.LO=545;
T20.LO=685; T21.LO=730; T22.LO=660;
T23.LO=660; T235.LO=665; T24.LO=500;
T25.LO=345; Tsbfw.LO=220; TSHP1.LO=660;
TSHP2.LO=645; TSW1.LO=335;
F06.UP=2.4; f50.UP=0.26; fsbfw.UP=1.95;
O2percent.UP=7; Pshp1.UP=700; Pshp2.UP=700;
Pss2.UP=715; SO2ppm.UP=380; T06.UP=364;
T07.UP=1325; T09.UP=650; T10.UP=715;
T11.UP=915; T12.UP=715; T13.UP=790;
T15.UP=505; T16.UP=355; T19.UP=555;
T20.UP=695; T21.UP=740; T22.UP=720;
T23.UP=720; T235.UP=680; T24.UP=510;
T25.UP=355; Tsbfw.UP=230; TSHP1.UP=670;
TSHP2.UP=655; TSW1.UP=345;
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ai1201.L=1.12; ai1202.L=0.757; ai1203.L=0.493;
ai1204.L=0.363; ai1205.L=0.318; aii1201.L=0.988;
aii1202.L=0.849; aii1203.L=0.72; aii1204.L=0.618;
aii1205.L=0.562; aiii1101.L=1.183; aiii1102.L=1.104;
aiii1103.L=1.032; aiii1104.L=0.971; aiii1105.L=0.928;
aiv1101.L=1.378; aiv1102.L=1.308; aiv1103.L=1.237;
aiv1104.L=1.168; aiv1105.L=1.113; blrdt.L=495;
bypass.L=0.097; ci1201.L=0.87; ci1202.L=1.357;
ci1203.L=2.207; ci1204.L=3.122; ci1205.L=3.631;
cii1201.L=1.003; cii1202.L=1.191; cii1203.L=1.437;
cii1204.L=1.708; cii1205.L=1.901; ciii1101.L=0.995;
ciii1102.L=1.102; ciii1103.L=1.218; ciii1104.L=1.332;
ciii1105.L=1.425; civ1101.L=0.793; civ1102.L=0.857;

civ1103.L=0.931; civ1104.L=1.014; civ1105.L=1.088;
clrdt.L=307.3; Cpi1.L=0.033; Cpi2.L=0.034;
Cpi3.L=0.035; Cpi4.L=0.036; Cpi5.L=0.036;
Cpii1.L=0.035; Cpii2.L=0.035; Cpii3.L=0.035;
Cpii4.L=0.036; Cpii5.L=0.036; Cpiii1.L=0.035;
Cpiii2.L=0.036; Cpiii3.L=0.036; Cpiii4.L=0.036;
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Cpiii5.L=0.036; Cpiv1.L=0.031; Cpiv2.L=0.031;
Cpiv3.L=0.031; Cpiv4.L=0.031; Cpiv5.L=0.031;
di1201.L=4.241; di1202.L=2.154; di1203.L=1.027;
di1204.L=0.606; di1205.L=0.481; dii1201.L=3.411;
dii1202.L=2.628; dii1203.L=1.973; dii1204.L=1.517;
dii1205.L=1.288; diii1101.L=3.929; diii1102.L=3.597;
diii1103.L=3.298; diii1104.L=3.052; diii1105.L=2.878;
div1101.L=4.783; div1102.L=4.471; div1103.L=4.163;
div1104.L=3.866; div1105.L=3.636; dti1.L=7.54;
dti2.L=11.244; dti3.L=13.234; dti4.L=8.884;
dti5.L=2.987; dtii1.L=3.229; dtii2.L=3.902;
dtii3.L=4.415; dtii4.L=3.96; dtii5.L=2.065;
dtiii1.L=0.68; dtiii2.L=0.705; dtiii3.L=0.688;
dtiii4.L=0.594; dtiii5.L=0.408; dtiv1.L=0.367;
dtiv2.L=0.394; dtiv3.L=0.422; dtiv4.L=0.439;
dtiv5.L=0.306; emiss.L=3.7; emiss1.L=0.0037;
enthi1.L=37.449; enthi2.L=42.166; enthi3.L=48.555;
enthi4.L=54.539; enthi5.L=57.842; enthii1.L=39.475;
enthii2.L=41.384; enthii3.L=43.645; enthii4.L=45.957;
enthii5.L=47.642; enthiii1.L=39.426; enthiii2.L=40.142;
enthiii3.L=40.865; enthiii4.L=41.534; enthiii5.L=42.06;
enthiv1.L=29.892; enthiv2.L=30.293; enthiv3.L=30.725;
enthiv4.L=31.182; enthiv5.L=31.58; ex65dT.L=100;
ex66dt.L=100; ex67dt.L=100; ex68dT.L=100;
ex71dT.L=100; f06n2.L=1.4; f06o2.L=0.35;
f07.L=1.74; f07n2.L=1.4; f07o2.L=0.103;
f07so2.L=0.24; f07so3.L=0.0049; f08.L=1.342;
f08a.L=0.408; f08an2.L=0.326; f08ao2.L=0.024;
f08aso2.L=0.056; f08aso3.L=0.0016; f08n2.L=1.074;
f08o2.L=0.079; f08so2.L=0.184; f08so3.L=0.0033;
f09.L=1.342; f09n2.L=1.074; f09o2.L=0.079;
f09so2.L=0.184; f09so3.L=0.0033; f10.L=1.75;
f10n2.L=1.4; f10o2.L=0.103; f10so2.L=0.24;
f10so3.L=0.0049; f11.L=1.7; f11n2.L=1.4;
f11o2.L=0.14; f11so2.L=0.0647; f11so3.L=0.11;
f12.L=1.7; f12n2.L=1.4; f12o2.L=0.14;
f12so2.L=0.0647; f12so3.L=0.11; f13.L=1.68;
f13n2.L=1.4; f13o2.L=0.118; f13so2.L=0.0262;
f13so3.L=0.151; f14.L=1.68; f14n2.L=1.4;
f14o2.L=0.118; f14so2.L=0.0262; f14so3.L=0.151;
f15.L=1.68; f15n2.L=1.4; f15o2.L=0.118;
f15so2.L=0.0262; f15so3.L=0.151; f16.L=1.53;
f16n2.L=1.4; f16o2.L=0.118; f16so2.L=0.0262;
f19.L=1.53; f19n2.L=1.4; f19o2.L=0.118;
f19so2.L=0.0262; f20.L=1.53; f20n2.L=1.4;
f20o2.L=0.118; f20so2.L=0.0262; f21.L=1.525;
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f21n2.L=1.4; f21o2.L=0.11; f21so2.L=0.01;
f21so3.L=0.076; f22.L=1.525; f22n2.L=1.4;
f22o2.L=0.11; f22so2.L=0.01; f22so3.L=0.01;
f23.L=1.52; f235.L=1.52; f235n2.L=1.4;
f235o2.L=0.106; f235so2.L=0.000456; f235so3.L=0.0257;
f23n2.L=1.4; f23o2.L=0.106; f23so2.L=0.000456;
f23so3.L=0.0257; f24.L=1.52; f24n2.L=1.4;
f24o2.L=0.106; f24so2.L=0.000456; f24so3.L=0.0257;
f25.L=1.52; f25n2.L=1.4; f25o2.L=0.106;
f25so2.L=0.000456; fdw.L=0.06; ffiiiso21.L=-0.009;
ffiiiso22.L=-0.009; ffiiiso23.L=-0.008; ffiiiso24.L=-0.007;
ffiiso21.L=-0.03; ffiiso22.L=-0.035; ffiiso23.L=-0.036;
ffiiso24.L=-0.026; ffiso21.L=-0.078; ffiso22.L=-0.106;
ffiso23.L=-0.1; ffiso24.L=-0.055; ffivso21.L=-0.004;
ffivso22.L=-0.005; ffivso23.L=-0.005; ffivso24.L=-0.004;
ffprod.L=0.1; fiiio21.L=0.135; fiiio22.L=0.132;
fiiio23.L=0.128; fiiio24.L=0.124; fiiio25.L=0.122;
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1466  fiiiso21.L=0.045; fiiiso22.L=0.038; fiiiso23.L=0.03;
1467  fiiiso24.L=0.023; fiiiso25.L=0.018; fiiiso31.L=0;
1468  fiiiso32.L=0.305; fiiiso33.L=0.313; fiiiso34.L=0.319;
1469  fiiiso35.L=0.325; fiiio21.L=0.177; fiiio22.L=0.167;
1470  fiio23.L=0.156; fiio24.L=0.144; fiio25.L=0.135;
1471  fiiso21.L=0.128; fiiso22.L=0.108; fiiso23.L=0.086;
1472  fiiso24.L=0.062; fiiso25.L=0.045; fiiso31.L=0.215;
1473  fiiso32.L=0.234; fiiso33.L=0.257; fiiso34.L=0.281;
1474  fiiso35.L=0.298; fio21.L=0.1; fio22.L=0.1;
1475  fio23.L=0.1; fio24.L=0.1; fio25.L=0.1;
1476  fiso21.L=0.336; fiso22.L=0.288; fiso23.L=0.223;
1477  fiso24.L=0.162; fiso25.L=0.128; fiso31.L=0.007;
1478  fiso32.L=0.055; fiso33.L=0.12; fiso34.L=0.181;
1479  fiso35.L=0.215; fivo21.L=0.122; fivo22.L=0.12;
1480  fivo23.L=0.118; fivo24.L=0.115; fivo25.L=0.113;
1481  fivso21.L=0.018; fivso22.L=0.014; fivso23.L=0.01;
1482  fivso24.L=0.005; fivso25.L=0.001; fivso31.L=0;
1483  fivso32.L=0.004; fivso33.L=0.008; fivso34.L=0.013;
1484  fivso35.L=0.017; fprod.L=0.1; fsbd.L=0.19;
1485  fshp1.L=0.8; fshp2.L=0.8; fss1.L=1.9;
1486  fss1a.L=0.8; fss1b.L=0.8; fss2.L=1.6;
1487  fss4.L=0.8; fss5.L=0.8; fsw1.L=1.9;
1488  fsw1a.L=0.8; fsw1b.L=0.8; Ftriiin21.L=3.198;
1489  Ftriiin22.L=3.219; Ftriiin23.L=3.241; Ftriiin24.L=3.26;
1490  Ftriiin25.L=3.275; Ftriiio21.L=2.79; Ftriiio22.L=2.808;
1491  Ftriiio23.L=2.827; Ftriiio24.L=2.845; Ftriiio25.L=2.858;
1492  Ftriiiso21.L=1.306; Ftriiiso22.L=1.317; Ftriiiso23.L=1.328;
1493  Ftriiiso24.L=1.338; Ftriiiso25.L=1.346; Ftriiiso31.L=1.168;
1494  Ftriiiso32.L=1.178; Ftriiiso33.L=1.188; Ftriiiso34.L=1.197;
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1495  Ftriiiso35.L=1.204; Ftriin21.L=3.2; Ftriin22.L=3.257;
1496  Ftriin23.L=3.322; Ftriin24.L=3.388; Ftriin25.L=3.435;
1497  Ftriio21.L=2.791; Ftriio22.L=2.841; Ftriio23.L=2.9;
1498  Ftriio24.L=2.958; Ftriio25.L=3; Ftriiso21.L=1.307;
1499  Ftriiso22.L=1.336; Ftriiso23.L=1.369; Ftriiso24.L=1.402;
1500  Ftriiso25.L=1.426; Ftriiso31.L=1.169; Ftriiso32.L=1.195;
1501  Ftriiso33.L=1.226; Ftriiso34.L=1.257; Ftriiso35.L=1.279;
1502  Ftrin21.L=3.14; Ftrin22.L=3.281; Ftrin23.L=3.463;
1503  Ftrin24.L=3.625; Ftrin25.L=3.712; Ftrio21.L=2.738;
1504  Ftrio22.L=2.863; Ftrio23.L=3.024; Ftrio24.L=3.168;
1505  Ftrio25.L=3.245; Ftriso21.L=1.277; Ftriso22.L=1.348;
1506  Ftriso23.L=1.44; Ftriso24.L=1.522; Ftriso25.L=1.565;
1507  Ftriso31.L=1.141; Ftriso32.L=1.207; Ftriso33.L=1.292;
1508  Ftriso34.L=1.368; Ftriso35.L=1.409; Ftrivn21.L=3.153;
1509  Ftrivn22.L=3.169; Ftrivn23.L=3.185; Ftrivn24.L=3.203;
1510  Ftrivn25.L=3.218; Ftrivo21.L=2.749; Ftrivo22.L=2.763;
1511  Ftrivo23.L=2.778; Ftrivo24.L=2.794; Ftrivo25.L=2.807;
1512  Ftrivso21.L=1.283; Ftrivso22.L=1.291; Ftrivso23.L=1.3;
1513  Ftrivso24.L=1.309; Ftrivso25.L=1.316; Ftrivso31.L=1.147;
1514  Ftrivso32.L=1.154; Ftrivso33.L=1.162; Ftrivso34.L=1.17;
1515  Ftrivso35.L=1.177; h06.L=2.261; h07.L=59.312;
1516  h08.L=45.576; h08a.L=13.735; h09.L=18.698;
1517  h10.L=33.308; h11.L=47.484; h12.L=33.92;
1518  h13.L=37.733; h14.L=30; h15.L=20;
1519  h16.L=15; h19.L=20; h20.L=35.816;
1520  h21.L=36.013; h22.L=34.659; h23.L=34.741;
1521  h235.L=26; h24.L=18.273; h25.L=6.42;
1522  h50.L=1.6; hrso2.L=314.845; hrso3.L=89.468;
1523  Hsbd.L=10; Hsbfw.L=10; Hshp1.L=10;
1524  Hshp2.L=10; Hslp.L=10; Hss1.L=10;
1525  Hss1a.L=10; hss1b.L=10; Hss2.L=10;
1526  Hss4.L=10; Hss5.L=10; Hsw1.L=10;
1527  Hsw1a.L=10; hsw1b.L=10; jhi1.L=0.114;
1528  jhi2.L=0.117; jhi3.L=0.12; jhi4.L=0.123;
1529  jhi5.L=0.125; jhii1.L=0.115; jhii2.L=0.116;
1530  jhii3.L=0.118; jhii4.L=0.119; jhii5.L=0.12;
1531  jhiii1.L=0.133; jhiii2.L=0.134; jhiii3.L=0.134;
1532  jhiii4.L=0.135; jhiii5.L=0.135; jhiv1.L=0.155;
1533  jhiv2.L=0.156; jhiv3.L=0.156; jhiv4.L=0.157;
1534  jhiv5.L=0.157; kpi1.L=290.141; kpi2.L=92.817;
1535  kpi3.L=26.685; kpi4.L=10.981; kpi5.L=7.454;
1536  kpii1.L=201.184; kpii2.L=129.697; kpii3.L=80.102;
1537  kpii4.L=51.499; kpii5.L=39.106; kpiii1.L=216.837;
1538  kpiii2.L=184.103; kpiii3.L=156.747; kpiii4.L=135.732;
1539  kpiii5.L=121.76; kpiv1.L=312.207; kpiv2.L=275.533;
1540  kpiv3.L=241.394; kpiv4.L=210.424; kpiv5.L=187.783;
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1541  Mfi1.L=508.689; Mfi2.L=508.689; Mfi3.L=508.689;
1542  Mfi4.L=508.689; Mfi5.L=508.689; Mfii1.L=508.689;
1543  Mfii2.L=508.689; Mfii3.L=508.689; Mfii4.L=508.689;
1544  Mfii5.L=508.689; Mfiii1.L=508.689; Mfiii2.L=508.689;
1545  Mfiii3.L=508.689; Mfiii4.L=508.689; Mfiii5.L=508.689;
1546  Mfiv1.L=373.146; Mfiv2.L=373.146; Mfiv3.L=373.146;
1547  Mfiv4.L=373.146; Mfiv5.L=373.146; mwprod.L=42.8;
1548  profit.L=0.1; Psbd.L=695; Pss1.L=695;
1549  Pss1a.L=695; Pss1b.L=695; Pss4.L=695;
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1550  Pss5.L=695; ratei1.L=0.008; ratei2.L=0.013;
1551  ratei3.L=0.016; ratei4.L=0.011; ratei5.L=0.004;
1552  rateii1.L=0.004; rateii2.L=0.005; rateii3.L=0.005;
1553  rateii4.L=0.005; rateii5.L=0.003; rateiii1.L=0.001;
1554  rateiii2.L=0.001; rateiii3.L=0.001; rateiii4.L=0.001;
1555  rateiii5.L=0.00082433; rateiniii1.L=0.013; rateiniii2.L=0.013;
1556  rateiniii3.L=0.013; rateiniii4.L=0.011; rateiniii5.L=0.008;
1557  rateinti1.L=0.035; rateinti2.L=0.054; rateinti3.L=0.067;
1558  rateinti4.L=0.047; rateinti5.L=0.016; rateintii1.L=0.023;
1559  rateintii2.L=0.028; rateintii3.L=0.033; rateintii4.L=0.03;
1560  rateintii5.L=0.016; rateintiv1.L=0.018; rateintiv2.L=0.019;
1561  rateintiv3.L=0.021; rateintiv4.L=0.022; rateintiv5.L=0.015;
1562  rateiv1.L=0.0006497; rateiv2.L=0.0007017; rateiv3.L=0.00075427;
1563  rateiv4.L=0.00078816; rateiv5.L=0.00055157; rheati1.L=44.79;
1564  rheati2.L=44.604; rheati3.L=44.338; rheati4.L=44.095;
1565  rheati5.L=43.971; rheatii1.L=44.735; rheatii2.L=44.663;
1566  rheatii3.L=44.576; rheatii4.L=44.488; rheatii5.L=44.428;
1567  rheatiii1.L=44.747; rheatiii2.L=44.721; rheatiii3.L=44.695;
1568  rheatiii4.L=44.671; rheatiii5.L=44.652; rheativ1.L=44.8;
1569  rheativ2.L=44.782; rheativ3.L=44.763; rheativ4.L=44.742;
1570  rheativ5.L=44.724; so2ppm1.L=0.355; T08.L=1321;
1571  T08a.L=1321; T14.L=600; Tcati1.L=699.574;
1572  Tcati2.L=750.224; Tcati3.L=814.739; Tcati4.L=867.905;
1573  Tcati5.L=893.341; Tcatii1.L=715.083; Tcatii2.L=734.611;
1574  Tcatii3.L=757.311; Tcatii4.L=779.389; Tcatii5.L=793.81;
1575  Tcatiii1.L=711.854; Tcatiii2.L=718.945; Tcatiii3.L=726.055;
1576  Tcatiii4.L=732.538; Tcatiii5.L=737.508; Tcativ1.L=696.549;
1577  Tcativ2.L=701.721; Tcativ3.L=707.28; Tcativ4.L=713.144;
1578  Tcativ5.L=718.08; tfi1.L=2.997; tfi2.L=2.973;
1579  tfi3.L=2.94; tfi4.L=2.91; tfi5.L=2.893;
1580  tfii1.L=2.893; tfii2.L=2.883; tfii3.L=2.872;
1581  tfii4.L=2.86; tfii5.L=2.851; tfiii1.L=2.851;
1582  tfiii2.L=2.848; tfiii3.L=2.844; tfiii4.L=2.841;
1583  tfiii5.L=2.838; tfiv1.L=2.513; tfiv2.L=2.511;
1584  tfiv3.L=2.509; tfiv4.L=2.507; tfiv5.L=2.505;
1585  Tgasi1.L=692.033; Tgasi2.L=738.98; Tgasi3.L=801.505;
1586  Tgasi4.L=859.021; Tgasi5.L=890.355; Tgasii1.L=711.854;
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1587  Tgasii2.L=730.709; Tgasii3.L=752.896; Tgasii4.L=775.429;
1588  Tgasii5.L=791.745; Tgasiii1.L=711.173; Tgasiii2.L=718.241;
1589  Tgasiii3.L=725.368; Tgasiii4.L=731.945; Tgasiii5.L=737.099;
1590  Tgasiv1.L=696.183; Tgasiv2.L=701.327; Tgasiv3.L=706.858;
1591  Tgasiv4.L=712.705; Tgasiv5.L=717.774; thhi1.L=7.693;
1592  thhi2.L=10.42; thhi3.L=9.76; thhi4.L=5.387;
1593  thhii1.L=2.939; thhii2.L=3.48; thhii3.L=3.559;
1594  thhii4.L=2.593; thhiii1.L=0.877; thhiii2.L=0.886;
1595  thhiii3.L=0.819; thhiii4.L=0.643; thhiv1.L=0.432;
1596  thhiv2.L=0.465; thhiv3.L=0.493; thhiv4.L=0.428;
1597  Triiin21.L=5.635; Triiin22.L=5.691; Triiin23.L=5.748;
1598  Triiin24.L=5.8; Triiin25.L=5.841; Triiio21.L=4.6;
1599  Triiio22.L=4.646; Triiio23.L=4.692; Triiio24.L=4.734;
1600  Triiio25.L=4.768; Triiiso21.L=1.653; Triiiso22.L=1.669;
1601  Triiiso23.L=1.685; Triiiso24.L=1.701; Triiiso25.L=1.713;
1602  Triiiso31.L=1.447; Triiiso32.L=1.461; Triiiso33.L=1.476;
1603  Triiiso34.L=1.489; Triiiso35.L=1.5; Triin21.L=5.641;
1604  Triin22.L=5.79; Triin23.L=5.966; Triin24.L=6.144;
1605  Triin25.L=6.274; Triio21.L=4.604; Triio22.L=4.726;
1606  Triio23.L=4.87; Triio24.L=5.016; Triio25.L=5.121;
1607  Triiso21.L=1.654; Triiso22.L=1.698; Triiso23.L=1.749;
1608  Triiso24.L=1.802; Triiso25.L=1.84; Triiso31.L=1.448;
1609  Triiso32.L=1.487; Triiso33.L=1.532; Triiso34.L=1.578;
1610  Triiso35.L=1.611; Trin21.L=5.484; Trin22.L=5.856;
1611  Trin23.L=6.351; Trin24.L=6.807; Trin25.L=7.055;
1612  Trio21.L=4.476; Trio22.L=4.78; Trio23.L=5.184;
1613  Trio24.L=5.556; Trio25.L=5.759; Triso21.L=1.608;
1614  Triso22.L=1.717; Triso23.L=1.862; Triso24.L=1.996;
1615  Triso25.L=2.069; Triso31.L=1.408; Triso32.L=1.504;
1616  Triso33.L=1.631; Triso34.L=1.748; Triso35.L=1.812;
1617  Trivn21.L=5.517; Trivn22.L=5.557; Trivn23.L=5.601;
1618  Trivn24.L=5.647; Trivn25.L=5.688; Trivo21.L=4.503;
1619  Trivo22.L=4.536; Trivo23.L=4.572; Trivo24.L=4.61;
1620  Trivo25.L=4.643; Trivso21.L=1.618; Trivso22.L=1.63;
1621  Trivso23.L=1.642; Trivso24.L=1.656; Trivso25.L=1.668;
1622  Trivso31.L=1.417; Trivso32.L=1.427; Trivso33.L=1.438;
1623  Trivso34.L=1.45; Trivso35.L=1.46; Tsbd.L=450;
1624  Tss1.L=450; Tss1a.L=450; Tss1b.L=450;
1625  Tss2.L=450; Tss4.L=450; Tss5.L=450;
1626  Tsw1a.L=340; Tsw1b.L=340; Visci1.L=0.14;
1627  Visci2.L=0.146; Visci3.L=0.155; Visci4.L=0.162;
1628  Visci5.L=0.166; Viscii1.L=0.142; Viscii2.L=0.145;
1629  Viscii3.L=0.148; Viscii4.L=0.151; Viscii5.L=0.153;
1630  Visciii1.L=0.142; Visciii2.L=0.143; Visciii3.L=0.144;
1631  Visciii4.L=0.145; Visciii5.L=0.146; Visciv1.L=0.141;
1632  Visciv2.L=0.141; Visciv3.L=0.142; Visciv4.L=0.143;
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1633  Visciv5.L=0.144; wbratio.L=0.77542; Xprod.L=0.41;
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ai1201.LO=0.001; ai1202.LO=0.001; ai1203.LO=0.001;
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aii1202.LO=0.001; aii1203.LO=0.001; aii1204.LO=0.001;
aii1205.LO=0.001; aiii1101.LO=0.001; aiii1102.LO=0.001;
aiii1103.LO=0.001; aiii1104.LO=0.001; aiii1105.LO=0.001;
aiv1101.LO=0.001; aiv1102.LO=0.001; aiv1103.LO=0.001;
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ci1203.LO=0.001; ci1204.LO=0.001; ci1205.LO=0.001;
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cii1204.LO=0.0005; cii1205.LO=0.0005; ciii1101.LO=0.0005;
ciii1102.LO=0.0005; ciii1103.LO=0.0005; ciii1104.LO=0.0005;
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civ1103.LO=0.0005; civ1104.LO=0.0005; civ1105.LO=0.0005;
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Cpii4.LO=0.001; Cpii5.LO=0.001; Cpiii1.LO=0.001;
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dii1202.LO=0.0005; dii1203.LO=0.0005; dii1204.LO=0.0005;
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diii1103.LO=0.0005; diii1104.LO=0.0005; diii1105.LO=0.0005;
div1101.LO=0.0005; div1102.LO=0.0005; div1103.LO=0.0005;
div1104.LO=0.0005; div1105.LO=0.0005; dti1.LO=0.01;
dti2.LO=0.01; dti3.LO=0.01; dti4.LO=0.01;
dti5.LO=0.01; dtii1.LO=0.01; dtii2.LO=0.01;
dtii3.LO=0.01; dtii4.LO=0.01; dtii5.LO=0.01;
dtiii1.LO=0.01; dtiii2.LO=0.01; dtiii3.LO=0.01;
dtiii4.LO=0.01; dtiii5.LO=0.01; dtiv1.LO=0.01;
dtiv2.LO=0.01; dtiv3.LO=0.01; dtiv4.LO=0.01;
dtiv5.LO=0.01; emiss.LO=0.1; emiss1.LO=0.0001;
enthi1.LO=0.1; enthi2.LO=0.1; enthi3.LO=0.1;
enthi4.LO=0.1; enthi5.LO=0.1; enthii1.LO=0.1;
enthii2.LO=0.1; enthii3.LO=0.1; enthii4.LO=0.1;
enthii5.LO=0.1; enthiii1.LO=0.1; enthiii2.LO=0.1;
enthiii3.LO=0.1; enthiii4.LO=0.1; enthiii5.LO=0.1;
enthiv1.LO=0.1; enthiv2.LO=0.1; enthiv3.LO=0.1;
enthiv4.LO=0.1; enthiv5.LO=0.1; ex65dT.LO=10;
ex66dt.LO=10; ex67dt.LO=10; ex68dT.LO=10;
ex71dT.LO=10; f06n2.LO=1.2; f06o2.LO=0.06;
f07.LO=1.2; f07n2.LO=1.2; f07o2.LO=0.0001;
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f07so2.LO=0.01; f07so3.LO=0.0024; f08.LO=0.6;
f08a.LO=0.00001; f08an2.LO=0.00001; f08ao2.LO=0.00001;
f08aso2.LO=0.00001; f08aso3.LO=0.00001; f08n2.LO=0.3;
f08o2.LO=0.006; f08so2.LO=0.006; f08so3.LO=0.0006;
f09.LO=0.6; f09n2.LO=0.3; f09o2.LO=0.006;
f09so2.LO=0.006; f09so3.LO=0.0006; f10.LO=1.2;
f10n2.LO=1.2; f10o2.LO=0.02; f10so2.LO=0.18;
f10so3.LO=0.0024; f11.LO=1.1; f11n2.LO=1.2;
f11o2.LO=0.001; f11so2.LO=0.01; f11so3.LO=0.02;
f12.LO=1.1; f12n2.LO=1.2; f12o2.LO=0.01;
f12so2.LO=0.01; f12so3.LO=0.02; f13.LO=1;
f13n2.LO=1.2; f13o2.LO=0.01; f13so2.LO=0.005;
f13so3.LO=0.05; f14.LO=1; f14n2.LO=1.2;
f14o2.LO=0.01; f14so2.LO=0.005; f14so3.LO=0.05;
f15.LO=1; f15n2.LO=1.2; f15o2.LO=0.01;
f15so2.LO=0.005; f15so3.LO=0.05; f16.LO=1;
f16n2.LO=1.2; f16o2.LO=0.01; f16so2.LO=0.005;
f19.LO=1; f19n2.LO=1.2; f19o2.LO=0.01;
f19so2.LO=0.005; f20.LO=1; f20n2.LO=1.2;
f20o2.LO=0.01; f20so2.LO=0.005; f21.LO=1;
f21n2.LO=1.2; f21o2.LO=0.001; f21so2.LO=0.005;
f21so3.LO=0.00001; f22.LO=0.5; f22n2.LO=1.2;
f22o2.LO=0.001; f22so2.LO=0.0001; f22so3.LO=0.0001;
f23.LO=1; f235.LO=1; f235n2.LO=1.2;
f235o2.LO=0.001; f235so2.LO=0.0001; f235so3.LO=0.01;
f23n2.LO=1.2; f23o2.LO=0.001; f23so2.LO=0.0001;
f23so3.LO=0.01; f24.LO=1; f24n2.LO=1.2;
f24o2.LO=0.005; f24so2.LO=0.0001; f24so3.LO=0.01;
f25.LO=1; f25n2.LO=1.2; f25o2.LO=0.005;
f25so2.LO=0.00001; fdw.LO=0.0001; ffprod.LO=0.0001;
fiiio21.LO=0.001; fiiio22.LO=0.001; fiiio23.LO=0.001;
fiiio24.LO=0.001; fiiio25.LO=0.001; fiiiso21.LO=0.0001;
fiiiso22.LO=0.0001; fiiiso23.LO=0.0001; fiiiso24.LO=0.0001;
fiiiso25.LO=0.0001; fiiiso31.LO=0; fiiiso32.LO=0.001;
fiiiso33.LO=0.001; fiiiso34.LO=0.001; fiiiso35.LO=0.001;
fiio21.LO=0.001; fiio22.LO=0.001; fiio23.LO=0.001;
fiio24.LO=0.001; fiio25.LO=0.001; fiiso21.LO=0.001;
fiiso22.LO=0.001; fiiso23.LO=0.001; fiiso24.LO=0.001;
fiiso25.LO=0.001; fiiso31.LO=0.001; fiiso32.LO=0.001;
fiiso33.LO=0.001; fiiso34.LO=0.001; fiiso35.LO=0.001;
fio21.LO=0.001; fio22.LO=0.001; fio23.LO=0.001;
fio24.LO=0.001; fio25.LO=0.001; fiso21.LO=0.001;
fiso22.LO=0.001; fiso23.LO=0.001; fiso24.LO=0.001;
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1722  fiso25.LO=0.001; fiso31.LO=0; fiso32.LO=0;
1723  fiso33.LO=0; fiso34.LO=0; fiso35.LO=0.001;
1724  fivo21.LO=0.001; fivo22.LO=0.001; fivo23.LO=0.001;

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1725  fivo24.LO=0.001; fivo25.LO=0.001; fivso21.LO=0.0001;
1726  fivso22.LO=0.0001; fivso23.LO=0.0001; fivso24.LO=0.0001;
1727  fivso25.LO=0.0001; fivso31.LO=0; fivso32.LO=0;
1728  fivso33.LO=0; fivso34.LO=0; fivso35.LO=0;
1729  fprod.LO=0.0001; fsbd.LO=0.1; fshp1.LO=0.1;
1730  fshp2.LO=0.1; fss1.LO=0.1; fss1a.LO=0.1;
1731  fss1b.LO=0.1; fss2.LO=0.1; fss4.LO=0.1;
1732  fss5.LO=0.1; fsw1.LO=0.1; fsw1a.LO=0.1;
1733  fsw1b.LO=0.1; h06.LO=0.01; h07.LO=0.01;
1734  h08.LO=0.01; h08a.LO=0.01; h09.LO=0.01;
1735  h10.LO=0.01; h11.LO=0.01; h12.LO=0.01;
1736  h13.LO=0.01; h14.LO=0.01; h15.LO=0.01;
1737  h16.LO=0.01; h19.LO=0.01; h20.LO=0.01;
1738  h21.LO=0.01; h22.LO=0.01; h23.LO=0.01;
1739  h235.LO=0.01; h24.LO=0.01; h25.LO=0.01;
1740  h50.LO=0.01; hrso2.LO=200; hrso3.LO=30;
1741  Hsbd.LO=0.01; Hsbfw.LO=0.01; Hshp1.LO=0.01;
1742  Hshp2.LO=0.01; Hslp.LO=0.01; Hss1.LO=0.01;
1743  Hss1a.LO=0.01; hss1b.LO=0.01; Hss2.LO=0.01;
1744  Hss4.LO=0.01; Hss5.LO=0.01; Hsw1.LO=0.01;
1745  Hsw1a.LO=0.01; hsw1b.LO=0.01; jhi1.LO=0.001;
1746  jhi2.LO=0.001; jhi3.LO=0.001; jhi4.LO=0.001;
1747  jhi5.LO=0.001; jhii1.LO=0.001; jhii2.LO=0.001;
1748  jhii3.LO=0.001; jhii4.LO=0.001; jhii5.LO=0.001;
1749  jhiii1.LO=0.001; jhiii2.LO=0.001; jhiii3.LO=0.001;
1750  jhiii4.LO=0.001; jhiii5.LO=0.001; jhiv1.LO=0.001;
1751  jhiv2.LO=0.001; jhiv3.LO=0.001; jhiv4.LO=0.001;
1752  jhiv5.LO=0.001; kpi1.LO=0.1; kpi2.LO=0.1;
1753  kpi3.LO=0.1; kpi4.LO=0.1; kpi5.LO=0.1;
1754  kpii1.LO=0.1; kpii2.LO=0.1; kpii3.LO=0.1;
1755  kpii4.LO=0.1; kpii5.LO=0.1; kpiii1.LO=0.1;
1756  kpiii2.LO=0.1; kpiii3.LO=0.1; kpiii4.LO=0.1;
1757  kpiii5.LO=0.1; kpiv1.LO=0.1; kpiv2.LO=0.1;
1758  kpiv3.LO=0.1; kpiv4.LO=0.1; kpiv5.LO=0.1;
1759  Mfi1.LO=15; Mfi2.LO=15; Mfi3.LO=15;
1760  Mfi4.LO=15; Mfi5.LO=15; Mfii1.LO=15.529;
1761  Mfii2.LO=15.529; Mfii3.LO=15.529; Mfii4.LO=15.529;
1762  Mfii5.LO=15.529; Mfiii1.LO=15.229; Mfiii2.LO=15.229;
1763  Mfiii3.LO=15.229; Mfiii4.LO=15.229; Mfiii5.LO=15.229;
1764  Mfiv1.LO=15.112; Mfiv2.LO=15.112; Mfiv3.LO=15.112;
1765  Mfiv4.LO=15.112; Mfiv5.LO=15.112; mwprod.LO=40;
1766  profit.LO=0; Psbd.LO=600; Pss1.LO=600;
1767  Pss1a.LO=600; Pss1b.LO=600; Pss4.LO=600;
1768  Pss5.LO=600; rateiniii1.LO=0.0005; rateiniii2.LO=0.0005;
1769  rateiniii3.LO=0.0005; rateiniii4.LO=0.0005; rateiniii5.LO=0.0005;
1770  rateinti1.LO=0.0005; rateinti2.LO=0.0005; rateinti3.LO=0.0005;
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1771  rateinti4.LO=0.0005; rateinti5.LO=0.0005; rateintii1.LO=0.005;
1772  rateintii2.LO=0.005; rateintii3.LO=0.005; rateintii4.LO=0.005;
1773  rateintii5.LO=0.005; rateintiv1.LO=0.0005; rateintiv2.LO=0.0005;
1774  rateintiv3.LO=0.0005; rateintiv4.LO=0.0005; rateintiv5.LO=0.0005;
1775  rheati1.LO=0.1; rheati2.LO=0.1; rheati3.LO=0.1;
1776  rheati4.LO=0.1; rheati5.LO=0.1; rheatii1.LO=1;
1777  rheatii2.LO=1; rheatii3.LO=1; rheatii4.LO=1;
1778  rheatii5.LO=1; rheatiii1.LO=0.1; rheatiii2.LO=0.1;
1779  rheatiii3.LO=0.1; rheatiii4.LO=0.1; rheatiii5.LO=0.1;
1780  rheativ1.LO=1; rheativ2.LO=1; rheativ3.LO=1;
1781  rheativ4.LO=1; rheativ5.LO=1; so2ppm1.LO=0.1;
1782  T08.LO=1000; T08a.LO=1000; T14.LO=500;
1783  Tcati1.LO=580.01; Tcati2.LO=625.26; Tcati3.LO=670.51;
1784  Tcati4.LO=715.76; Tcati5.LO=761.01; Tcatii1.LO=606.01;
1785  Tcatii2.LO=625.26; Tcatii3.LO=644.51; Tcatii4.LO=663.76;
1786  Tcatii5.LO=683.01; Tcatiii1.LO=601.827; Tcatiii2.LO=609.373;
1787  Tcatiii3.LO=616.918; Tcatiii4.LO=624.464; Tcatiii5.LO=632.01;
1788  Tcativ1.LO=588.01; Tcativ2.LO=594.26; Tcativ3.LO=600.51;
1789  Tcativ4.LO=606.76; Tcativ5.LO=613.01; tfi1.LO=0.001;
1790  tfi2.LO=0.001; tfi3.LO=0.001; tfi4.LO=0.001;
1791  tfi5.LO=0.001; tfii1.LO=0.103; tfii2.LO=0.103;
1792  tfii3.LO=0.103; tfii4.LO=0.103; tfii5.LO=0.103;
1793  tfiii1.LO=0.102; tfiii2.LO=0.102; tfiii3.LO=0.102;
1794  tfiii4.LO=0.102; tfiii5.LO=0.102; tfiv1.LO=0.102;
1795  tfiv2.LO=0.102; tfiv3.LO=0.102; tfiv4.LO=0.102;
1796  tfiv5.LO=0.102; Tgasi1.LO=580; Tgasi2.LO=625.25;
1797  Tgasi3.LO=670.5; Tgasi4.LO=715.75; Tgasi5.LO=761;
1798  Tgasii1.LO=606; Tgasii2.LO=625.25; Tgasii3.LO=644.5;
1799  Tgasii4.LO=663.75; Tgasii5.LO=683; Tgasiii1.LO=601.817;
1800  Tgasiii2.LO=609.363; Tgasiii3.LO=616.908; Tgasiii4.LO=624.454;
1801  Tgasiii5.LO=632; Tgasiv1.LO=588; Tgasiv2.LO=594.25;
1802  Tgasiv3.LO=600.5; Tgasiv4.LO=606.75; Tgasiv5.LO=613;
1803  thhi1.LO=0.01; thhi2.LO=0.01; thhi3.LO=0.01;
1804  thhi4.LO=0.01; thhii1.LO=0.01; thhii2.LO=0.01;
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1805  thhii3.LO=0.01; thhii4.LO=0.01; thhiii1.LO=0.01;
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1807  thhiv1.LO=0.01; thhiv2.LO=0.01; thhiv3.LO=0.01;
1808  thhiv4.LO=0.01; Triiin21.LO=4.769; Triiin22.LO=4.829;
1809  Triiin23.LO=4.888; Triiin24.LO=4.948; Triiin25.LO=5.008;
1810  Triiio21.LO=3.893; Triiio22.LO=3.942; Triiio23.LO=3.99;
1811  Triiio24.LO=4.039; Triiio25.LO=4.088; Triiiso21.LO=1.398;
1812  Triiiso22.LO=1.416; Triiiso23.LO=1.433; Triiiso24.LO=1.451;
1813  Triiiso25.LO=1.469; Triiiso31.LO=1.225; Triiiso32.LO=1.24;
1814  Triiiso33.LO=1.255; Triiiso34.LO=1.271; Triiiso35.LO=1.286;
1815  Triin21.LO=4.802; Triin22.LO=4.954; Triin23.LO=5.107;
1816  Triin24.LO=5.26; Triin25.LO=5.412; Triio21.LO=3.92;
Economic Optimization Program                                   01/25/01 17:27:26  PAGE     41
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1817  Triio22.LO=4.044; Triio23.LO=4.169; Triio24.LO=4.293;
1818  Triio25.LO=4.418; Triiso21.LO=1.408; Triiso22.LO=1.453;
1819  Triiso23.LO=1.498; Triiso24.LO=1.542; Triiso25.LO=1.587;
1820  Triiso31.LO=1.233; Triiso32.LO=1.272; Triiso33.LO=1.311;
1821  Triiso34.LO=1.351; Triiso35.LO=1.39; Trin21.LO=4.596;
1822  Trin22.LO=4.954; Trin23.LO=5.313; Trin24.LO=5.672;
1823  Trin25.LO=6.03; Trio21.LO=3.752; Trio22.LO=4.044;
1824  Trio23.LO=4.337; Trio24.LO=4.63; Trio25.LO=4.922;
1825  Triso21.LO=1.348; Triso22.LO=1.453; Triso23.LO=1.558;
1826  Triso24.LO=1.663; Triso25.LO=1.768; Triso31.LO=1.18;
1827  Triso32.LO=1.272; Triso33.LO=1.364; Triso34.LO=1.456;
1828  Triso35.LO=1.548; Trivn21.LO=4.659; Trivn22.LO=4.709;
1829  Trivn23.LO=4.758; Trivn24.LO=4.808; Trivn25.LO=4.857;
1830  Trivo21.LO=3.803; Trivo22.LO=3.844; Trivo23.LO=3.884;
1831  Trivo24.LO=3.925; Trivo25.LO=3.965; Trivso21.LO=1.366;
1832  Trivso22.LO=1.381; Trivso23.LO=1.395; Trivso24.LO=1.41;
1833  Trivso25.LO=1.424; Trivso31.LO=1.196; Trivso32.LO=1.209;
1834  Trivso33.LO=1.222; Trivso34.LO=1.235; Trivso35.LO=1.247;
1835  Tsbd.LO=100; Tss1.LO=100; Tss1a.LO=100;
1836  Tss1b.LO=100; Tss2.LO=100; Tss4.LO=100;
1837  Tss5.LO=100; Tsw1a.LO=100; Tsw1b.LO=100;
1838  Visci1.LO=0.001; Visci2.LO=0.001; Visci3.LO=0.001;
1839  Visci4.LO=0.001; Visci5.LO=0.001; Viscii1.LO=0.001;
1840  Viscii2.LO=0.001; Viscii3.LO=0.001; Viscii4.LO=0.001;
1841  Viscii5.LO=0.001; Visciii1.LO=0.001; Visciii2.LO=0.001;
1842  Visciii3.LO=0.001; Visciii4.LO=0.001; Visciii5.LO=0.001;
1843  Visciv1.LO=0.001; Visciv2.LO=0.001; Visciv3.LO=0.001;
1844  Visciv4.LO=0.001; Visciv5.LO=0.001; wbratio.LO=0.01;
1845  Xprod.LO=0.4;
1846  blrdt.UP=1000; bypass.UP=1; clrdt.UP=1000;
1847  emiss.UP=4; emiss1.UP=0.004; f06n2.UP=2.4;
1848  f06o2.UP=0.6; f07.UP=2.4; f07n2.UP=1.8;
1849  f07o2.UP=0.6; f07so2.UP=0.3; f07so3.UP=0.0072;
1850  f08.UP=4; f08a.UP=1.2; f08an2.UP=0.6;
1851  f08ao2.UP=0.1; f08aso2.UP=0.6; f08aso3.UP=0.06;
1852  f08n2.UP=2.4; f08o2.UP=0.6; f08so2.UP=0.6;
1853  f08so3.UP=0.012; f09.UP=4; f09n2.UP=4;
1854  f09o2.UP=0.6; f09so2.UP=0.6; f09so3.UP=0.012;
1855  f10.UP=2.4; f10n2.UP=1.8; f10o2.UP=0.6;
1856  f10so2.UP=0.3; f10so3.UP=0.0072; f11.UP=2.5;
1857  f11n2.UP=1.8; f11o2.UP=0.4; f11so2.UP=1;
1858  f11so3.UP=0.18; f12.UP=2.5; f12n2.UP=1.8;
1859  f12o2.UP=0.22; f12so2.UP=1; f12so3.UP=0.18;
1860  f13.UP=3; f13n2.UP=1.8; f13o2.UP=0.2;
1861  f13so2.UP=1; f13so3.UP=0.5; f14.UP=3;
1862  f14n2.UP=1.8; f14o2.UP=0.2; f14so2.UP=1;
Economic Optimization Program                                   01/25/01 17:27:26  PAGE     42
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1863  f14so3.UP=0.5; f15.UP=3; f15n2.UP=1.8;
1864  f15o2.UP=0.2; f15so2.UP=1; f15so3.UP=0.5;
1865  f16.UP=3; f16n2.UP=1.8; f16o2.UP=0.2;
1866  f16so2.UP=1; f19.UP=3; f19n2.UP=1.8;
1867  f19o2.UP=0.2; f19so2.UP=1; f20.UP=3;
1868  f20n2.UP=1.8; f20o2.UP=0.2; f20so2.UP=1;
1869  f21.UP=3; f21n2.UP=1.8; f21o2.UP=0.2;
1870  f21so2.UP=1; f21so3.UP=0.1; f22.UP=3;
1871  f22n2.UP=1.8; f22o2.UP=0.2; f22so2.UP=1;
1872  f22so3.UP=0.1; f23.UP=3; f235.UP=3;
1873  f235n2.UP=1.8; f235o2.UP=0.2; f235so2.UP=1;
1874  f235so3.UP=0.1; f23n2.UP=1.8; f23o2.UP=0.2;
1875  f23so2.UP=1; f23so3.UP=0.1; f24.UP=3;
1876  f24n2.UP=1.8; f24o2.UP=0.2; f24so2.UP=1;
1877  f24so3.UP=0.1; f25.UP=3; f25n2.UP=1.8;
1878  f25o2.UP=0.2; f25so2.UP=1; ffiiiso21.UP=0;
1879  ffiiiso22.UP=0; ffiiiso23.UP=0; ffiiiso24.UP=0;
1880  ffiiso21.UP=0; ffiiso22.UP=0; ffiiso23.UP=0;
1881  ffiiso24.UP=0; ffiso21.UP=0; ffiso22.UP=0;
1882  ffiso23.UP=0; ffiso24.UP=0; ffivso21.UP=0;
1883  ffivso22.UP=0; ffivso23.UP=0; ffivso24.UP=0;
1884  hrso2.UP=500; hrso3.UP=150; mwprod.UP=45;
1885  Psbd.UP=900; Pss1.UP=900; Pss1a.UP=900;
1886  Pss1b.UP=900; Pss4.UP=900; Pss5.UP=900;
1887  so2ppm1.UP=0.38; T08.UP=1500; T08a.UP=1500;
1888  T14.UP=800; Tgasi1.UP=797; Tgasi2.UP=842.25;
```

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1889  Tgasi3.UP=887.5; Tgasi4.UP=932.75; Tgasi5.UP=978;
1890  Tgasii1.UP=823; Tgasii2.UP=842.25; Tgasii3.UP=861.5;
1891  Tgasii4.UP=880.75; Tgasii5.UP=900; Tgasiii1.UP=818;
1892  Tgasiii2.UP=825.75; Tgasiii3.UP=833.5; Tgasiii4.UP=841.25;
1893  Tgasiii5.UP=849; Tgasiv1.UP=805; Tgasiv2.UP=811.25;
1894  Tgasiv3.UP=817.5; Tgasiv4.UP=823.75; Tgasiv5.UP=830;
1895  Triiin21.UP=6.482; Triiin22.UP=6.543; Triiin23.UP=6.605;
1896  Triiin24.UP=6.666; Triiin25.UP=6.727; Triiio21.UP=5.291;
1897  Triiio22.UP=5.341; Triiio23.UP=5.391; Triiio24.UP=5.441;
1898  Triiio25.UP=5.492; Triiiso21.UP=1.901; Triiiso22.UP=1.919;
1899  Triiiso23.UP=1.937; Triiiso24.UP=1.955; Triiiso25.UP=1.973;
1900  Triiiso31.UP=1.664; Triiiso32.UP=1.68; Triiiso33.UP=1.696;
1901  Triiiso34.UP=1.712; Triiiso35.UP=1.728; Triin21.UP=6.521;
1902  Triin22.UP=6.674; Triin23.UP=6.826; Triin24.UP=6.979;
1903  Triin25.UP=7.132; Triio21.UP=5.323; Triio22.UP=5.448;
1904  Triio23.UP=5.572; Triio24.UP=5.697; Triio25.UP=5.821;
1905  Triiso21.UP=1.912; Triiso22.UP=1.957; Triiso23.UP=2.002;
1906  Triiso24.UP=2.047; Triiso25.UP=2.091; Triiso31.UP=1.675;
1907  Triiso32.UP=1.714; Triiso33.UP=1.753; Triiso34.UP=1.792;
1908  Triiso35.UP=1.831; Trin21.UP=6.315; Trin22.UP=6.674;
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1909  Trin23.UP=7.032; Trin24.UP=7.391; Trin25.UP=7.75;
1910  Trio21.UP=5.155; Trio22.UP=5.448; Trio23.UP=5.741;
1911  Trio24.UP=6.033; Trio25.UP=6.326; Triso21.UP=1.852;
1912  Triso22.UP=1.957; Triso23.UP=2.062; Triso24.UP=2.167;
1913  Triso25.UP=2.273; Triso31.UP=1.622; Triso32.UP=1.714;
1914  Triso33.UP=1.806; Triso34.UP=1.898; Triso35.UP=1.99;
1915  Trivn21.UP=6.379; Trivn22.UP=6.428; Trivn23.UP=6.478;
1916  Trivn24.UP=6.527; Trivn25.UP=6.577; Trivo21.UP=5.207;
1917  Trivo22.UP=5.247; Trivo23.UP=5.288; Trivo24.UP=5.328;
1918  Trivo25.UP=5.369; Trivso21.UP=1.871; Trivso22.UP=1.885;
1919  Trivso23.UP=1.9; Trivso24.UP=1.914; Trivso25.UP=1.929;
1920  Trivso31.UP=1.638; Trivso32.UP=1.651; Trivso33.UP=1.663;
1921  Trivso34.UP=1.676; Trivso35.UP=1.689; Tsbd.UP=700;
1922  Tss1.UP=700; Tss1a.UP=700; Tss1b.UP=700;
1923  Tss2.UP=700; Tss4.UP=700; Tss5.UP=700;
1924  Tsw1a.UP=700; Tsw1b.UP=700; wbratio.UP=1;
1925  Xprod.UP=0.42;
1926
1927  MODEL Contact /ALL/;
1928  OPTION LIMCOL=0;
1929  OPTION LIMROW=0;
1930  OPTION ITERLIM= 1000;
1931  OPTION DOMLIM= 0;
1932  OPTION RESLIM= 1000;
1933  OPTION DOMLIM=10;
1934  OPTION NLP=CONOPT;
1935  SOLVE Contact Using NLP Maximizing ObjVar;
1936


COMPILATION TIME     =        0.160 SECONDS     1.1 Mb      WIN-18-097
Economic Optimization Program                                        01/25/01 17:27:26  PAGE     44
Model Statistics    SOLVE CONTACT USING NLP FROM LINE 1935                      GAMS 2.50A    Windows NT/95/98



MODEL STATISTICS

BLOCKS OF EQUATIONS      766     SINGLE EQUATIONS       766
BLOCKS OF VARIABLES      779     SINGLE VARIABLES       779
NON ZERO ELEMENTS       2639     NON LINEAR N-Z        1122
DERIVATIVE POOL           16     CONSTANT POOL          168
CODE LENGTH            41189


GENERATION TIME      =        0.160 SECONDS     1.8 Mb      WIN-18-097


EXECUTION TIME       =        0.220 SECONDS     1.8 Mb      WIN-18-097
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               S O L V E      S U M M A R Y

     MODEL   CONTACT             OBJECTIVE  OBJVAR
     TYPE    NLP                 DIRECTION  MAXIMIZE
     SOLVER  CONOPT              FROM LINE  1935

**** SOLVER STATUS     1 NORMAL COMPLETION
**** MODEL STATUS      2 LOCALLY OPTIMAL
**** OBJECTIVE VALUE                0.3077

 RESOURCE USAGE, LIMIT          6.809      1000.000
 ITERATION COUNT, LIMIT       595          1000
 EVALUATION ERRORS              0            10
```

```
     C O N O P T   Wintel  version 2.042F-003-035
     Copyright (C) ARKI Consulting and Development A/S
                   Bagsvaerdvej 246 A
                   DK-2880 Bagsvaerd, Denmark

 Using default control program.


 ** Optimal solution. Reduced gradient less than tolerance.


 CONOPT time Total                      6.809 seconds
   of which: Function evaluations        1.988 = 29.2%
             Derivative evaluations      0.227 =  3.3%

 Work length =    1.35 Mbytes
    Estimate =    1.35 Mbytes
    Max used =    0.63 Mbytes

                          LOWER          LEVEL          UPPER         MARGINAL

---- EQU EQU1               .              .              .             EPS
---- EQU EQU2               .              .              .       -5.633708E-5
---- EQU EQU3               .              .              .            -1.8976
---- EQU EQU4               .              .              .             EPS
---- EQU EQU5           -255.3722      -255.3722      -255.3722          EPS
---- EQU EQU6               .              .              .             0.0002
---- EQU EQU7             -0.9839        -0.9839        -0.9839   2.6189516E-5
---- EQU EQU8               .              .              .       -2.618952E-5
---- EQU EQU9               .              .              .             EPS
---- EQU EQU10              .              .              .             0.0427
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                          LOWER          LEVEL          UPPER         MARGINAL

---- EQU EQU11              .              .              .            -0.1775
---- EQU EQU12              .              .              .            -1.9795
---- EQU EQU13              .              .              .            -0.0915
---- EQU EQU14           102.4027       102.4027       102.4027          EPS
---- EQU EQU15              .              .              .            -0.0001
---- EQU EQU16              .              .              .             0.1740
---- EQU EQU17              .              .              .            -0.0461
---- EQU EQU18              .              .              .             1.8921
---- EQU EQU19              .              .              .       -5.633708E-5
---- EQU EQU20              .              .              .             0.0051
---- EQU EQU21            -5.2452        -5.2452        -5.2452   -5.633708E-5
---- EQU EQU22              .              .              .             1.9720
---- EQU EQU23           297.2528       297.2528       297.2528          EPS
---- EQU EQU24              .              .              .             2.3737
---- EQU EQU25              .              .              .             EPS
---- EQU EQU26              .              .              .             0.0002
---- EQU EQU27            -0.2341        -0.2341        -0.2341        -0.0051
---- EQU EQU28              .              .              .             1.6340
---- EQU EQU29              .              .              .             0.0373
---- EQU EQU30              .              .              .             EPS
---- EQU EQU31              .              .              .            -0.0051
---- EQU EQU32              .              .              .             0.0027
---- EQU EQU33              .              .              .             1.6948
---- EQU EQU34              .              .              .             0.0779
---- EQU EQU35              .              .              .             0.0886
---- EQU EQU36              .              .              .             0.0078
---- EQU EQU37              .              .              .             0.0467
---- EQU EQU38             0.2658         0.2658         0.2658         0.3032
---- EQU EQU39              .              .              .             EPS
---- EQU EQU40              .              .              .             EPS
---- EQU EQU41              .              .              .            -1.3873
---- EQU EQU42              .              .              .            -0.0020
---- EQU EQU43              .              .              .             EPS
---- EQU EQU44              .              .              .            -0.1030
---- EQU EQU45              .              .              .             EPS
---- EQU EQU46              .              .              .             EPS
---- EQU EQU47          -255.3722      -255.3722      -255.3722          EPS
---- EQU EQU48              .              .              .            -0.0002
---- EQU EQU49            -0.2850        -0.2850        -0.2850   2.6189516E-5
---- EQU EQU50              .              .              .       -2.618952E-5
---- EQU EQU51              .              .              .            -0.0005
---- EQU EQU52              .              .              .            -2.0914
---- EQU EQU53              .              .              .             EPS
---- EQU EQU54              .              .              .            -0.0095
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                          LOWER          LEVEL          UPPER         MARGINAL

---- EQU EQU55              .              .              .            -0.0915
---- EQU EQU56              .              .              .             0.0179
---- EQU EQU57              .              .              .             0.0033
---- EQU EQU58              .              .              .            -1.6751
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---- EQU EQU59         .         .         .          -0.0007
---- EQU EQU60         .         .         .           0.0509
---- EQU EQU61         .         .         .      -7.669918E-5
---- EQU EQU62         .         .         .             EPS
---- EQU EQU63         .         .         .      5.8521446E-5
---- EQU EQU64         .         .         .      2.7222375E-5
---- EQU EQU65         .         .         .      -2.013724E-5
---- EQU EQU66         .         .         .             EPS
---- EQU EQU67         .         .         .             EPS
---- EQU EQU68         .         .         .             EPS
---- EQU EQU69         .         .         .             EPS
---- EQU EQU70         .         .         .           1.7666
---- EQU EQU71         .         .         .          -0.3437
---- EQU EQU72         .         .         .          -0.2859
---- EQU EQU73         .         .         .             EPS
---- EQU EQU74         .         .         .             EPS
---- EQU EQU75         .         .         .             EPS
---- EQU EQU76         .         .         .             EPS
---- EQU EQU77         .         .         .          -0.0008
---- EQU EQU78         .         .         .          -0.0013
---- EQU EQU79      18.0000   18.0000   18.0000       0.0130
---- EQU EQU80         .         .         .           1.0000
---- EQU EQU81         .         .         .             EPS
---- EQU EQU82         .         .         .             EPS
---- EQU EQU83         .         .         .          -0.0012
---- EQU EQU84         .         .         .             EPS
---- EQU EQU85         .         .         .             EPS
---- EQU EQU86         .         .         .             EPS
---- EQU EQU87         .         .         .             EPS
---- EQU EQU88         .         .         .             EPS
---- EQU EQU89         .         .         .      -4.414952E-5
---- EQU EQU90         .         .         .             EPS
---- EQU EQU91         .         .         .          -0.0011
---- EQU EQU92         .         .         .             EPS
---- EQU EQU93         .         .         .             EPS
---- EQU EQU94         .         .         .             EPS
---- EQU EQU95         .         .         .             EPS
---- EQU EQU96         .         .         .             EPS
---- EQU EQU97         .         .         .             EPS
---- EQU EQU98         .         .         .             EPS
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                    LOWER     LEVEL     UPPER    MARGINAL

---- EQU EQU99         .         .         .             EPS
---- EQU EQU100        .         .         .             EPS
---- EQU EQU101        .         .         .          -0.1258
---- EQU EQU102        .         .         .          -0.0153
---- EQU EQU103        .         .         .          -0.0041
---- EQU EQU104        .         .         .          -0.0009
---- EQU EQU105        .         .         .          -0.0024
---- EQU EQU106        .         .         .          -0.0023
---- EQU EQU107        .         .         .             EPS
---- EQU EQU108        .         .         .          -0.0006
---- EQU EQU109        .         .         .          -0.0160
---- EQU EQU110        .         .         .          -0.1168
---- EQU EQU111        .         .         .          -0.0004
---- EQU EQU112        .         .         .          -0.0008
---- EQU EQU113        .         .         .          -0.0011
---- EQU EQU114        .         .         .          -0.0004
---- EQU EQU115        .         .         .             EPS
---- EQU EQU116        .         .         .             EPS
---- EQU EQU117        .         .         .          -0.0022
---- EQU EQU118        .         .         .           0.1006
---- EQU EQU119        .         .         .      2.0519724E-5
---- EQU EQU120        .         .         .             EPS
---- EQU EQU121        .         .         .           0.2693
---- EQU EQU122        .         .         .           0.4650
---- EQU EQU123        .         .         .           0.3957
---- EQU EQU124        .         .         .           0.5339
---- EQU EQU125        .         .         .           0.3240
---- EQU EQU126        .         .         .          -0.1351
---- EQU EQU127        .         .         .           0.1182
---- EQU EQU128        .         .         .          -0.0159
---- EQU EQU129        .         .         .           0.1357
---- EQU EQU130        .         .         .          -0.2662
---- EQU EQU131        .         .         .           0.0823
---- EQU EQU132        .         .         .          -0.0002
---- EQU EQU133        .         .         .          -0.0007
---- EQU EQU134        .         .         .          -0.0012
---- EQU EQU135        .         .         .          -0.0013
---- EQU EQU136        .         .         .          -0.0003
---- EQU EQU137        .         .         .          -0.0014
---- EQU EQU138        .         .         .          -0.0023
---- EQU EQU139        .         .         .          -0.0026
---- EQU EQU140        .         .         .          -0.0011
---- EQU EQU141        .         .         .          -0.0008
---- EQU EQU142        .         .         .          -0.0003
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                    LOWER      LEVEL      UPPER     MARGINAL

---- EQU EQU143        .          .          .        -0.0016
---- EQU EQU144        .          .          .     4.2424239E-5
---- EQU EQU145        .          .          .     4.2549358E-5
---- EQU EQU146        .          .          .     8.4172500E-5
---- EQU EQU147        .          .          .     6.3213918E-5
---- EQU EQU148        .          .          .     2.1332798E-5
---- EQU EQU149        .          .          .     -3.549680E-5
---- EQU EQU150        .          .          .     4.2549358E-5
---- EQU EQU151        .          .          .     8.4172500E-5
---- EQU EQU152        .          .          .     6.3213918E-5
---- EQU EQU153        .          .          .     2.1332798E-5
---- EQU EQU154        .          .          .     -3.549680E-5
---- EQU EQU155      46.4466    46.4466    46.4466        EPS
---- EQU EQU156      46.4466    46.4466    46.4466  -2.043466E-5
---- EQU EQU157      46.4466    46.4466    46.4466  -7.292234E-5
---- EQU EQU158      46.4466    46.4466    46.4466      -0.0001
---- EQU EQU159      46.4466    46.4466    46.4466  -3.881647E-5
---- EQU EQU160        .          .          .        -0.0048
---- EQU EQU161        .          .          .        -0.0119
---- EQU EQU162        .          .          .        -0.0110
---- EQU EQU163        .          .          .        -0.0039
---- EQU EQU164        .          .          .         0.0037
---- EQU EQU165        .          .          .         EPS
---- EQU EQU166        .          .          .         EPS
---- EQU EQU167        .          .          .         EPS
---- EQU EQU168        .          .          .         EPS
---- EQU EQU169        .          .          .         EPS
---- EQU EQU170        .          .          .        -0.0014
---- EQU EQU171        .          .          .        -0.0035
---- EQU EQU172        .          .          .        -0.0033
---- EQU EQU173        .          .          .        -0.0012
---- EQU EQU174        .          .          .         0.0011
---- EQU EQU175        .          .          .        -0.0006
---- EQU EQU176        .          .          .        -0.0015
---- EQU EQU177        .          .          .        -0.0014
---- EQU EQU178        .          .          .        -0.0005
---- EQU EQU179        .          .          .         0.0004
---- EQU EQU180        .          .          .         EPS
---- EQU EQU181        .          .          .         EPS
---- EQU EQU182        .          .          .         EPS
---- EQU EQU183        .          .          .         EPS
---- EQU EQU184        .          .          .         EPS
---- EQU EQU185        .          .          .         EPS
---- EQU EQU186        .          .          .     -2.026771E-5
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                    LOWER      LEVEL      UPPER     MARGINAL

---- EQU EQU187        .          .          .         EPS
---- EQU EQU188        .          .          .         EPS
---- EQU EQU189        .          .          .         EPS
---- EQU EQU190        .          .          .         EPS
---- EQU EQU191        .          .          .         EPS
---- EQU EQU192        .          .          .         EPS
---- EQU EQU193        .          .          .         EPS
---- EQU EQU194        .          .          .         EPS
---- EQU EQU195        .          .          .         EPS
---- EQU EQU196        .          .          .         EPS
---- EQU EQU197        .          .          .         EPS
---- EQU EQU198        .          .          .         EPS
---- EQU EQU199        .          .          .         EPS
---- EQU EQU200        .          .          .         EPS
---- EQU EQU201        .          .          .         EPS
---- EQU EQU202        .          .          .         EPS
---- EQU EQU203        .          .          .         EPS
---- EQU EQU204        .          .          .         EPS
---- EQU EQU205        .          .          .     -2.162257E-5
---- EQU EQU206        .          .          .     -5.347765E-5
---- EQU EQU207        .          .          .     -4.938664E-5
---- EQU EQU208        .          .          .         EPS
---- EQU EQU209        .          .          .         EPS
---- EQU EQU210        .          .          .         EPS
---- EQU EQU211        .          .          .         EPS
---- EQU EQU212        .          .          .         EPS
---- EQU EQU213        .          .          .         EPS
---- EQU EQU214        .          .          .         EPS
---- EQU EQU215        .          .          .         EPS
---- EQU EQU216        .          .          .         EPS
---- EQU EQU217        .          .          .         EPS
---- EQU EQU218        .          .          .         EPS
---- EQU EQU219        .          .          .         EPS
---- EQU EQU220        .          .          .         0.5955
---- EQU EQU221        .          .          .         1.0602
---- EQU EQU222        .          .          .         0.8308
---- EQU EQU223        .          .          .         0.7623
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---- EQU EQU224          .         .         .          0.3673
---- EQU EQU225          .         .         .          0.1423
---- EQU EQU226          .         .         .          0.2533
---- EQU EQU227          .         .         .          0.1985
---- EQU EQU228          .         .         .          0.1821
---- EQU EQU229          .         .         .          0.0877
---- EQU EQU230          .         .         .         -0.0031
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                       LOWER          LEVEL          UPPER         MARGINAL

---- EQU EQU231          .         .         .         -0.0081
---- EQU EQU232          .         .         .         -0.0094
---- EQU EQU233          .         .         .         -0.0106
---- EQU EQU234          .         .         .         -0.0032
---- EQU EQU235          .         .         .         -0.0004
---- EQU EQU236          .         .         .         -0.0011
---- EQU EQU237          .         .         .         -0.0013
---- EQU EQU238          .         .         .         -0.0015
---- EQU EQU239          .         .         .         -0.0005
---- EQU EQU240          .         .         .         -0.0003
---- EQU EQU241          .         .         .         -0.0008
---- EQU EQU242          .         .         .         -0.0010
---- EQU EQU243          .         .         .         -0.0013
---- EQU EQU244          .         .         .         -0.0004
---- EQU EQU245          .         .         .          EPS
---- EQU EQU246          .         .         .          EPS
---- EQU EQU247          .         .         .          EPS
---- EQU EQU248          .         .         .      2.7831795E-5
---- EQU EQU249          .         .         .      5.8194104E-5
---- EQU EQU250          .         .         .         -0.0375
---- EQU EQU251          .         .         .         -0.0464
---- EQU EQU252          .         .         .         -1.6325
---- EQU EQU253          .         .         .         -2.2900
---- EQU EQU254          .         .         .         -0.0002
---- EQU EQU255          .         .         .          0.0042
---- EQU EQU256          .         .         .         -0.0539
---- EQU EQU257          .         .         .          1.4861
---- EQU EQU258          .         .         .          1.9831
---- EQU EQU259          .         .         .         -0.3001
---- EQU EQU260          .         .         .         -0.3148
---- EQU EQU261          .         .         .         -0.3342
---- EQU EQU262          .         .         .         -0.3598
---- EQU EQU263          .         .         .         -0.5359
---- EQU EQU264          .         .         .         -0.5621
---- EQU EQU265          .         .         .         -0.5968
---- EQU EQU266          .         .         .         -0.6425
---- EQU EQU267          .         .         .          0.0004
---- EQU EQU268          .         .         .          0.0003
---- EQU EQU269          .         .         .          0.0002
---- EQU EQU270          .         .         .          EPS
---- EQU EQU271          .         .         .         -0.0539
---- EQU EQU272          .         .         .         -0.0358
---- EQU EQU273          .         .         .         -0.0202
---- EQU EQU274          .         .         .         -0.0064
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                       LOWER          LEVEL          UPPER         MARGINAL

---- EQU EQU275          .         .         .          1.9952
---- EQU EQU276          .         .         .          2.0568
---- EQU EQU277          .         .         .          2.1197
---- EQU EQU278          .         .         .          2.1793
---- EQU EQU279          .         .         .          0.0048
---- EQU EQU280          .         .         .          0.0027
---- EQU EQU281          .         .         .          0.0019
---- EQU EQU282          .         .         .          0.0012
---- EQU EQU283          .         .         .          0.0006
---- EQU EQU284          .         .         .          0.0048
---- EQU EQU285          .         .         .          0.0034
---- EQU EQU286          .         .         .          0.0022
---- EQU EQU287          .         .         .          0.0011
---- EQU EQU288          .         .         .         -0.0014
---- EQU EQU289          .         .         .         -0.0012
---- EQU EQU290          .         .         .         -0.0011
---- EQU EQU291          .         .         .         -0.0002
---- EQU EQU292          .         .         .      4.6830565E-5
---- EQU EQU293          .         .         .      4.6865517E-5
---- EQU EQU294          .         .         .      8.4528376E-5
---- EQU EQU295          .         .         .      7.2244920E-5
---- EQU EQU296          .         .         .      6.5343159E-5
---- EQU EQU297          .         .         .          EPS
---- EQU EQU298          .         .         .      4.6865517E-5
---- EQU EQU299          .         .         .      8.4528376E-5
---- EQU EQU300          .         .         .      7.2244920E-5
---- EQU EQU301          .         .         .      6.5343159E-5
---- EQU EQU302          .         .         .          EPS
---- EQU EQU303          .         .         .         -0.2473
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---- EQU EQU304          .          .          .          -0.1624
---- EQU EQU305          .          .          .          -0.0057
---- EQU EQU306          .          .          .            EPS
---- EQU EQU307          .          .          .           0.0684
---- EQU EQU308       46.4466    46.4466    46.4466   -7.685483E-5
---- EQU EQU309          .          .          .            EPS
---- EQU EQU310          .          .          .       4.6595634E-5
---- EQU EQU311          .          .          .            EPS
---- EQU EQU312          .          .          .       -5.340770E-5
---- EQU EQU313          .          .          .       -5.774041E-5
---- EQU EQU314       46.4466    46.4466    46.4466        EPS
---- EQU EQU315          .          .          .       -5.774041E-5
---- EQU EQU316       46.4466    46.4466    46.4466       -0.0001
---- EQU EQU317          .          .          .       -5.340770E-5
---- EQU EQU318       46.4466    46.4466    46.4466        EPS

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                        LOWER      LEVEL      UPPER     MARGINAL

---- EQU EQU319          .          .          .          -0.0106
---- EQU EQU320          .          .          .          -0.0187
---- EQU EQU321          .          .          .          -0.0012
---- EQU EQU322          .          .          .           0.0146
---- EQU EQU323          .          .          .           0.0068
---- EQU EQU324          .          .          .            EPS
---- EQU EQU325       46.4466    46.4466    46.4466   -6.983457E-5
---- EQU EQU326          .          .          .          -0.0006
---- EQU EQU327          .          .          .          -0.0003
---- EQU EQU328          .          .          .          -0.0006
---- EQU EQU329          .          .          .          -0.0006
---- EQU EQU330          .          .          .          -0.0003
---- EQU EQU331          .          .          .          -0.0006
---- EQU EQU332          .          .          .          -0.0012
---- EQU EQU333          .          .          .       3.3903986E-5
---- EQU EQU334          .          .          .          -0.0006
---- EQU EQU335          .          .          .            EPS
---- EQU EQU336          .          .          .       -3.925641E-5
---- EQU EQU337          .          .          .           0.0007
---- EQU EQU338          .          .          .           0.0008
---- EQU EQU339          .          .          .       3.3644772E-5
---- EQU EQU340          .          .          .       3.3903986E-5
---- EQU EQU341          .          .          .       4.6595634E-5
---- EQU EQU342          .          .          .            EPS
---- EQU EQU343          .          .          .          -0.0013
---- EQU EQU344          .          .          .            EPS
---- EQU EQU345          .          .          .            EPS
---- EQU EQU346          .          .          .           2.0392
---- EQU EQU347          .          .          .           0.0372
---- EQU EQU348          .          .          .           2.0277
---- EQU EQU349          .          .          .           0.0593
---- EQU EQU350          .          .          .           0.0601
---- EQU EQU351          .          .          .           2.0926
---- EQU EQU352          .          .          .            EPS
---- EQU EQU353          .          .          .           2.0965
---- EQU EQU354          .          .          .            EPS
---- EQU EQU355          .          .          .            EPS
---- EQU EQU356          .          .          .            EPS
---- EQU EQU357          .          .          .            EPS
---- EQU EQU358          .          .          .       -2.829432E-5
---- EQU EQU359          .          .          .            EPS
---- EQU EQU360          .          .          .          -0.0006
---- EQU EQU361          .          .          .           0.0510
---- EQU EQU362          .          .          .          -0.0022
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                        LOWER      LEVEL      UPPER     MARGINAL

---- EQU EQU363          .          .          .            EPS
---- EQU EQU364          .          .          .            EPS
---- EQU EQU365          .          .          .          -0.0030
---- EQU EQU366          .          .          .          -0.0053
---- EQU EQU367          .          .          .          -0.0003
---- EQU EQU368          .          .          .           0.0042
---- EQU EQU369          .          .          .           2.0759
---- EQU EQU370          .          .          .          -0.0013
---- EQU EQU371          .          .          .            EPS
---- EQU EQU372          .          .          .          -0.0001
---- EQU EQU373          .          .          .           0.0016
---- EQU EQU374          .          .          .           0.0008
---- EQU EQU375          .          .          .          -0.0006
---- EQU EQU376          .          .          .          -2.0914
---- EQU EQU377          .          .          .       2.6524231E-5
---- EQU EQU378          .          .          .           0.0020
---- EQU EQU379          .          .          .          -0.0095
---- EQU EQU380          .          .          .           0.0003
---- EQU EQU381          .          .          .          -0.0002
---- EQU EQU382          .          .          .            EPS
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---- EQU EQU383             .           .           .          -1.6751
---- EQU EQU384             .           .           .          -0.0179
---- EQU EQU385             .           .           .          -1.6812
---- EQU EQU386             .           .           .          -0.0125
---- EQU EQU387             .           .           .          -0.0033
---- EQU EQU388             .           .           .           0.0005
---- EQU EQU389             .           .           .          -2.1007
---- EQU EQU390             .           .           .           EPS
---- EQU EQU391             .           .           .           EPS
---- EQU EQU392             .           .           .           EPS
---- EQU EQU393             .           .           .          -0.1030
---- EQU EQU394             .           .           .          -0.1030
---- EQU EQU395             .           .           .           EPS
---- EQU EQU396             .           .           .           0.0002
---- EQU EQU397             .           .           .           EPS
---- EQU EQU398             .           .           .          -0.6284
---- EQU EQU399             .           .           .           EPS
---- EQU EQU400             .           .           .           EPS
---- EQU EQU401             .           .           .          -2.2804
---- EQU EQU402             .           .           .          -0.0919
---- EQU EQU403          -0.2088     -0.2088     -0.2088         EPS
---- EQU EQU404             .           .           .           0.0002
---- EQU EQU405           0.2088      0.2088      0.2088         EPS
---- EQU EQU406        -255.3737   -255.3737   -255.3737         EPS
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                        LOWER        LEVEL        UPPER       MARGINAL

---- EQU EQU407             .           .           .       2.6189516E-5
---- EQU EQU408             .           .           .           0.6284
---- EQU EQU409             .           .           .          -0.0002
---- EQU EQU410             .           .           .          -0.0002
---- EQU EQU411             .           .           .          -0.0002
---- EQU EQU412             .           .           .          -0.0002
---- EQU EQU413             .           .           .          -0.1719
---- EQU EQU414             .           .           .           0.0483
---- EQU EQU415             .           .           .          -1.8920
---- EQU EQU416             .           .           .          -1.9740
---- EQU EQU417             .           .           .          -0.0002
---- EQU EQU418             .           .           .           EPS
---- EQU EQU419             .           .           .           EPS
---- EQU EQU420             .           .           .          -0.0056
---- EQU EQU421             .           .           .          -0.0056
---- EQU EQU422             .           .           .            .
---- EQU EQU423          -0.1810     -0.1810     -0.1810       -0.0004
---- EQU EQU424             .           .           .           0.0003
---- EQU EQU425             .           .           .           0.0038
---- EQU EQU426             .           .           .           1.6325
---- EQU EQU427             .           .           .           0.0464
---- EQU EQU428             .           .           .           0.0004
---- EQU EQU429             .           .           .           EPS
---- EQU EQU430             .           .           .           EPS
---- EQU EQU431             .           .           .          -0.0037
---- EQU EQU432             .           .           .           0.0375
---- EQU EQU433             .           .           .           2.2900
---- EQU EQU434             .           .           .           0.0047
---- EQU EQU435             .           .           .           0.0052
---- EQU EQU436             .           .           .           0.0107
---- EQU EQU437             .           .           .           0.0025
---- EQU EQU438             .           .           .           1.5817
---- EQU EQU439             .           .           .           EPS
---- EQU EQU440             .           .           .           0.0303
---- EQU EQU441             .           .           .           0.0396
---- EQU EQU442             .           .           .           1.6242
---- EQU EQU443             .           .           .          -0.0363
---- EQU EQU444             .           .           .          -0.0005
---- EQU EQU445             .           .           .          -0.0002
---- EQU EQU446             .           .           .           1.9795
---- EQU EQU447             .           .           .           1.8976
---- EQU EQU448             .           .           .           0.1775
---- EQU EQU449             .           .           .          -0.0427
---- EQU EQU450             .           .           .           EPS
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                        LOWER        LEVEL        UPPER       MARGINAL

---- EQU EQU451             .           .           .           0.0927
---- EQU EQU452             .           .           .           EPS
---- EQU EQU453             .           .           .           EPS
---- EQU EQU454             .           .           .          -0.0102
---- EQU EQU455             .           .           .           2.2092
---- EQU EQU456             .           .           .          -0.0058
---- EQU EQU457             .           .           .           EPS
---- EQU EQU458             .           .           .       -2.819236E-5
---- EQU EQU459             .           .           .          -0.1030
---- EQU EQU460             .           .           .           1.4766
---- EQU EQU461        -255.3737   -255.3737   -255.3737         EPS
---- EQU EQU462           0.0618      0.0618      0.0618       -0.0009
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---- EQU EQU463         -0.0618      -0.0618      -0.0618        EPS
---- EQU EQU464            .            .            .           EPS
---- EQU EQU465       -255.3737    -255.3737    -255.3737        EPS
---- EQU EQU466            .            .            .         2.2804
---- EQU EQU467            .            .            .        -0.0002
---- EQU EQU468            .            .            .         0.6284
---- EQU EQU469            .            .            .        -0.0002
---- EQU EQU470            .            .            .        -0.1030
---- EQU EQU471            .            .            .           EPS
---- EQU EQU472          0.0141       0.0141       0.0141        EPS
---- EQU EQU473            .            .            .           EPS
---- EQU EQU474            .            .            .           EPS
---- EQU EQU475         -0.0141      -0.0141      -0.0141        EPS
---- EQU EQU476            .            .            .           EPS
---- EQU EQU477            .            .            .           EPS
---- EQU EQU478            .            .            .           EPS
---- EQU EQU479            .            .            .           EPS
---- EQU EQU480            .            .            .           EPS
---- EQU EQU481            .            .            .           EPS
---- EQU EQU482            .            .            .           EPS
---- EQU EQU483            .            .            .           EPS
---- EQU EQU484            .            .            .        -0.0919
---- EQU EQU485            .            .            .     2.6189516E-5
---- EQU EQU486            .            .            .     2.6189516E-5
---- EQU EQU487            .            .            .         0.0012
---- EQU EQU488            .            .            .           EPS
---- EQU EQU489            .            .            .        -0.0056
---- EQU EQU490            .            .            .           EPS
---- EQU EQU491            .            .            .        -0.0054
---- EQU EQU492            .            .            .         1.4772
---- EQU EQU493            .            .            .         2.2099
---- EQU EQU494            .            .            .        -0.5089
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                  LOWER        LEVEL        UPPER       MARGINAL

---- EQU EQU495            .            .            .        -0.5258
---- EQU EQU496            .            .            .        -0.5614
---- EQU EQU497            .            .            .        -0.6897
---- EQU EQU498            .            .            .        -0.7430
---- EQU EQU499            .            .            .        -0.7676
---- EQU EQU500            .            .            .        -0.8195
---- EQU EQU501            .            .            .        -1.0069
---- EQU EQU502            .            .            .     -3.688165E-5
---- EQU EQU503            .            .            .     -7.866398E-5
---- EQU EQU504            .            .            .        -0.0001
---- EQU EQU505            .            .            .     -9.576257E-5
---- EQU EQU506            .            .            .         0.0004
---- EQU EQU507            .            .            .           EPS
---- EQU EQU508            .            .            .        -0.0056
---- EQU EQU509            .            .            .        -0.0056
---- EQU EQU510            .            .            .         0.0123
---- EQU EQU511            .            .            .        -0.2200
---- EQU EQU512            .            .            .        -0.2310
---- EQU EQU513            .            .            .        -0.2446
---- EQU EQU514            .            .            .        -0.2769
---- EQU EQU515            .            .            .        -0.4210
---- EQU EQU516            .            .            .        -0.4422
---- EQU EQU517            .            .            .        -0.4681
---- EQU EQU518            .            .            .        -0.5299
---- EQU EQU519            .            .            .         0.0027
---- EQU EQU520            .            .            .         0.0014
---- EQU EQU521            .            .            .         0.0003
---- EQU EQU522            .            .            .        -0.0004
---- EQU EQU523            .            .            .         0.0124
---- EQU EQU524            .            .            .         0.0265
---- EQU EQU525            .            .            .         0.0363
---- EQU EQU526            .            .            .         0.0332
---- EQU EQU527            .            .            .         2.1093
---- EQU EQU528            .            .            .         2.1566
---- EQU EQU529            .            .            .         2.1968
---- EQU EQU530            .            .            .         2.2255
---- EQU EQU531            .            .            .        -0.0003
---- EQU EQU532         46.4466      46.4466      46.4466   2.7507626E-5
---- EQU EQU533         46.4466      46.4466      46.4466   5.2655664E-5
---- EQU EQU534         46.4466      46.4466      46.4466   3.9797771E-5
---- EQU EQU535         46.4466      46.4466      46.4466   2.6444576E-5
---- EQU EQU536         46.4466      46.4466      46.4466        EPS
---- EQU EQU537            .            .            .        -0.0016
---- EQU EQU538            .            .            .        -0.0031
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                  LOWER        LEVEL        UPPER       MARGINAL

---- EQU EQU539            .            .            .        -0.0029
---- EQU EQU540            .            .            .        -0.0029
---- EQU EQU541            .            .            .        -0.0009
---- EQU EQU542            .            .            .           EPS
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---- EQU EQU543            .          .          .          EPS
---- EQU EQU544            .          .          .          EPS
---- EQU EQU545            .          .          .          EPS
---- EQU EQU546            .          .          .          EPS
---- EQU EQU547            .          .          .         -0.0003
---- EQU EQU548            .          .          .         -0.0006
---- EQU EQU549            .          .          .         -0.0006
---- EQU EQU550            .          .          .         -0.0006
---- EQU EQU551            .          .          .         -0.0002
---- EQU EQU552            .          .          .         -0.0002
---- EQU EQU553            .          .          .         -0.0004
---- EQU EQU554            .          .          .         -0.0003
---- EQU EQU555            .          .          .         -0.0003
---- EQU EQU556            .          .          .      -9.699030E-5
---- EQU EQU557            .          .          .          EPS
---- EQU EQU558            .          .          .          EPS
---- EQU EQU559            .          .          .          EPS
---- EQU EQU560            .          .          .          EPS
---- EQU EQU561            .          .          .          EPS
---- EQU EQU562            .          .          .          EPS
---- EQU EQU563            .          .          .          EPS
---- EQU EQU564            .          .          .          EPS
---- EQU EQU565            .          .          .          EPS
---- EQU EQU566            .          .          .          EPS
---- EQU EQU567            .          .          .          EPS
---- EQU EQU568            .          .          .          EPS
---- EQU EQU569            .          .          .          EPS
---- EQU EQU570            .          .          .          EPS
---- EQU EQU571            .          .          .          EPS
---- EQU EQU572            .          .          .          EPS
---- EQU EQU573            .          .          .          EPS
---- EQU EQU574            .          .          .          EPS
---- EQU EQU575            .          .          .          EPS
---- EQU EQU576            .          .          .          EPS
---- EQU EQU577            .          .          .          EPS
---- EQU EQU578            .          .          .          EPS
---- EQU EQU579            .          .          .          EPS
---- EQU EQU580            .          .          .          EPS
---- EQU EQU581            .          .          .          EPS
---- EQU EQU582            .          .          .          EPS
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                       LOWER      LEVEL      UPPER      MARGINAL

---- EQU EQU583            .          .          .          EPS
---- EQU EQU584            .          .          .          EPS
---- EQU EQU585            .          .          .          EPS
---- EQU EQU586            .          .          .          EPS
---- EQU EQU587            .          .          .          EPS
---- EQU EQU588            .          .          .          EPS
---- EQU EQU589            .          .          .          EPS
---- EQU EQU590            .          .          .          EPS
---- EQU EQU591            .          .          .          EPS
---- EQU EQU592            .          .          .          EPS
---- EQU EQU593            .          .          .          EPS
---- EQU EQU594            .          .          .          EPS
---- EQU EQU595            .          .          .          EPS
---- EQU EQU596            .          .          .          EPS
---- EQU EQU597            .          .          .          1.3920
---- EQU EQU598            .          .          .          2.6218
---- EQU EQU599            .          .          .          2.3420
---- EQU EQU600            .          .          .          2.1361
---- EQU EQU601            .          .          .          1.0183
---- EQU EQU602            .          .          .          0.1185
---- EQU EQU603            .          .          .          0.2232
---- EQU EQU604            .          .          .          0.1993
---- EQU EQU605            .          .          .          0.1818
---- EQU EQU606            .          .          .          0.0867
---- EQU EQU607            .          .          .         -0.0034
---- EQU EQU608            .          .          .         -0.0077
---- EQU EQU609            .          .          .         -0.0081
---- EQU EQU610            .          .          .         -0.0088
---- EQU EQU611            .          .          .         -0.0045
---- EQU EQU612            .          .          .         -0.0005
---- EQU EQU613            .          .          .         -0.0011
---- EQU EQU614            .          .          .         -0.0011
---- EQU EQU615            .          .          .         -0.0012
---- EQU EQU616            .          .          .         -0.0006
---- EQU EQU617            .          .          .      -6.030403E-5
---- EQU EQU618            .          .          .      -2.728279E-5
---- EQU EQU619            .          .          .          EPS
---- EQU EQU620            .          .          .         -0.0001
---- EQU EQU621            .          .          .      -7.275701E-5
---- EQU EQU622            .          .          .          EPS
---- EQU EQU623            .          .          .          EPS
---- EQU EQU624            .          .          .          EPS
---- EQU EQU625            .          .          .          EPS
---- EQU EQU626            .          .          .          EPS
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                    LOWER       LEVEL       UPPER      MARGINAL

---- EQU EQU627          .           .           .         0.0058
---- EQU EQU628          .           .           .        -1.4766
---- EQU EQU629          .           .           .        -2.2092
---- EQU EQU630          .           .           .         EPS
---- EQU EQU631          .           .           .        -0.0009
---- EQU EQU632          .           .           .         0.0102
---- EQU EQU633          .           .           .        -0.0056
---- EQU EQU634          .           .           .        -0.0018
---- EQU EQU635          .           .           .         0.0013
---- EQU EQU636          .           .           .         0.0028
---- EQU EQU637          .           .           .         2.2131
---- EQU EQU638          .           .           .         2.2286
---- EQU EQU639          .           .           .         2.2453
---- EQU EQU640          .           .           .         2.2659
---- EQU EQU641          .           .           .         0.0008
---- EQU EQU642          .           .           .         0.0006
---- EQU EQU643          .           .           .         0.0003
---- EQU EQU644          .           .           .         0.0001
---- EQU EQU645          .           .           .     -4.503277E-5
---- EQU EQU646          .           .           .         0.0008
---- EQU EQU647          .           .           .         0.0005
---- EQU EQU648          .           .           .         0.0002
---- EQU EQU649          .           .           .     -6.574128E-5
---- EQU EQU650          .           .           .        -0.0003
---- EQU EQU651          .           .           .        -0.0003
---- EQU EQU652          .           .           .        -0.0002
---- EQU EQU653          .           .           .     6.5741276E-5
---- EQU EQU654          .           .           .         EPS
---- EQU EQU655          .           .           .         EPS
---- EQU EQU656          .           .           .         EPS
---- EQU EQU657          .           .           .         EPS
---- EQU EQU658          .           .           .         EPS
---- EQU EQU659          .           .           .         EPS
---- EQU EQU660          .           .           .         EPS
---- EQU EQU661          .           .           .         EPS
---- EQU EQU662          .           .           .         EPS
---- EQU EQU663          .           .           .         EPS
---- EQU EQU664          .           .           .         EPS
---- EQU EQU665       46.4466     46.4466     46.4466        EPS
---- EQU EQU666       46.4466     46.4466     46.4466        EPS
---- EQU EQU667       46.4466     46.4466     46.4466        EPS
---- EQU EQU668       46.4466     46.4466     46.4466        EPS
---- EQU EQU669       46.4466     46.4466     46.4466        EPS
---- EQU EQU670          .           .           .     -8.017402E-5
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                    LOWER       LEVEL       UPPER      MARGINAL

---- EQU EQU671          .           .           .        -0.0002
---- EQU EQU672          .           .           .        -0.0001
---- EQU EQU673          .           .           .        -0.0001
---- EQU EQU674          .           .           .         EPS
---- EQU EQU675          .           .           .         EPS
---- EQU EQU676          .           .           .         EPS
---- EQU EQU677          .           .           .         EPS
---- EQU EQU678          .           .           .         EPS
---- EQU EQU679          .           .           .         EPS
---- EQU EQU680          .           .           .         EPS
---- EQU EQU681          .           .           .     -3.189307E-5
---- EQU EQU682          .           .           .     -2.883605E-5
---- EQU EQU683          .           .           .         EPS
---- EQU EQU684          .           .           .     -2.066902E-5
---- EQU EQU685          .           .           .         EPS
---- EQU EQU686          .           .           .         EPS
---- EQU EQU687          .           .           .         EPS
---- EQU EQU688          .           .           .         EPS
---- EQU EQU689          .           .           .         EPS
---- EQU EQU690          .           .           .         EPS
---- EQU EQU691          .           .           .         EPS
---- EQU EQU692          .           .           .         EPS
---- EQU EQU693          .           .           .         EPS
---- EQU EQU694          .           .           .         EPS
---- EQU EQU695          .           .           .         EPS
---- EQU EQU696          .           .           .         EPS
---- EQU EQU697          .           .           .         EPS
---- EQU EQU698          .           .           .         EPS
---- EQU EQU699          .           .           .         EPS
---- EQU EQU700          .           .           .         EPS
---- EQU EQU701          .           .           .         EPS
---- EQU EQU702          .           .           .         EPS
---- EQU EQU703          .           .           .         EPS
---- EQU EQU704          .           .           .         EPS
---- EQU EQU705          .           .           .         EPS
---- EQU EQU706          .           .           .         EPS
---- EQU EQU707          .           .           .         EPS
---- EQU EQU708          .           .           .         EPS
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---- EQU EQU709          .          .          .          EPS
---- EQU EQU710          .          .          .          EPS
---- EQU EQU711          .          .          .          EPS
---- EQU EQU712          .          .          .          EPS
---- EQU EQU713          .          .          .          EPS
---- EQU EQU714          .          .          .          EPS
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                       LOWER      LEVEL      UPPER      MARGINAL

---- EQU EQU715          .          .          .          EPS
---- EQU EQU716          .          .          .          EPS
---- EQU EQU717          .          .          .          EPS
---- EQU EQU718          .          .          .          EPS
---- EQU EQU719          .          .          .          EPS
---- EQU EQU720          .          .          .          EPS
---- EQU EQU721          .          .          .          EPS
---- EQU EQU722          .          .          .          EPS
---- EQU EQU723          .          .          .          EPS
---- EQU EQU724          .          .          .          EPS
---- EQU EQU725          .          .          .          EPS
---- EQU EQU726          .          .          .          EPS
---- EQU EQU727          .          .          .          EPS
---- EQU EQU728          .          .          .          EPS
---- EQU EQU729          .          .          .          EPS
---- EQU EQU730          .          .          .          1.3695
---- EQU EQU731          .          .          .          2.7233
---- EQU EQU732          .          .          .          2.7418
---- EQU EQU733          .          .          .          3.0437
---- EQU EQU734          .          .          .          1.6503
---- EQU EQU735          .          .          .          0.0459
---- EQU EQU736          .          .          .          0.0912
---- EQU EQU737          .          .          .          0.0918
---- EQU EQU738          .          .          .          0.1019
---- EQU EQU739          .          .          .          0.0553
---- EQU EQU740          .          .          .         -0.0007
---- EQU EQU741          .          .          .         -0.0014
---- EQU EQU742          .          .          .         -0.0014
---- EQU EQU743          .          .          .         -0.0015
---- EQU EQU744          .          .          .         -0.0005
---- EQU EQU745          .          .          .     -8.046805E-5
---- EQU EQU746          .          .          .         -0.0002
---- EQU EQU747          .          .          .         -0.0002
---- EQU EQU748          .          .          .         -0.0002
---- EQU EQU749          .          .          .     -5.587371E-5
---- EQU EQU750          .          .          .          EPS
---- EQU EQU751          .          .          .     -2.108169E-5
---- EQU EQU752          .          .          .     -2.251484E-5
---- EQU EQU753          .          .          .     -2.440131E-5
---- EQU EQU754          .          .          .          EPS
---- EQU EQU755          .          .          .          EPS
---- EQU EQU756          .          .          .          EPS
---- EQU EQU757          .          .          .          EPS
---- EQU EQU758          .          .          .          EPS

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                       LOWER      LEVEL      UPPER      MARGINAL

---- EQU EQU759          .          .          .          EPS
---- EQU EQU760          .          .          .          0.0002
---- EQU EQU761          .          .          .          0.0002
---- EQU EQU762          .          .          .         -0.6284
---- EQU EQU763          .          .          .         -2.2804
---- EQU EQU764          .          .          .          EPS
---- EQU EQU765          .          .          .          EPS
---- EQU OBJNAME          .          .          .          1.0000

                       LOWER      LEVEL      UPPER      MARGINAL

---- VAR F06             1.7000     2.2077     2.4000         .
---- VAR F50             0.2200     0.2440     0.2600         .
---- VAR FSBFW             1.9100     1.9500     1.9500     0.0851
---- VAR O2PERCENT           5.0000     5.3128     7.0000       .
---- VAR PSHP1           550.0000   700.0000   700.0000       EPS
---- VAR PSHP2           550.0000   700.0000   700.0000       EPS
---- VAR PSS2           700.0000   712.5188   715.0000        .
---- VAR SO2PPM            100.0000   380.0000   380.0000       EPS
---- VAR T06            355.0000   355.0000   364.0000      EPS
---- VAR T07           1315.0000  1321.8456  1325.0000        .
---- VAR T09            640.0000   650.0000   650.0000      EPS
---- VAR T10            690.0000   712.6556   715.0000        .
---- VAR T11            890.0000   892.2150   915.0000        .
---- VAR T12            685.0000   692.2116   715.0000        .
---- VAR T13            780.0000   784.0652   790.0000        .
---- VAR T15            495.0000   505.0000   505.0000      0.0007
---- VAR T16            345.0000   345.0000   355.0000     -0.0004
---- VAR T19            545.0000   548.2427   555.0000        .
```

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---- VAR T20              685.0000     695.0000     695.0000       0.0002
---- VAR T21              730.0000     736.0289     740.0000        .
---- VAR T22              660.0000     684.6452     720.0000        .
---- VAR T23              660.0000     693.3908     720.0000        .
---- VAR T235             665.0000     674.5118     680.0000        .
---- VAR T24              500.0000     506.8174     510.0000        .
---- VAR T25              345.0000     350.4341     355.0000       EPS
---- VAR TSBFW            220.0000     226.6977     230.0000        .
---- VAR TSHP1            660.0000     670.0000     670.0000       EPS
---- VAR TSHP2            645.0000     655.0000     655.0000       EPS
---- VAR TSW1             335.0000     339.8194     345.0000        .
---- VAR OBJVAR             -INF         0.3077       +INF          .
---- VAR AI1201             0.0010       0.9276       +INF          .
---- VAR AI1202             0.0010       0.6433       +INF          .
---- VAR AI1203             0.0010       0.4521       +INF          .
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                         LOWER        LEVEL        UPPER       MARGINAL

---- VAR AI1204             0.0010       0.3533       +INF          .
---- VAR AI1205             0.0010       0.3131       +INF          .
---- VAR AII1201            0.0010       1.1535       +INF          .
---- VAR AII1202            0.0010       0.9829       +INF          .
---- VAR AII1203            0.0010       0.8123       +INF          .
---- VAR AII1204            0.0010       0.6669       +INF          .
---- VAR AII1205            0.0010       0.5848       +INF          .
---- VAR AIII1101           0.0010       1.3855       +INF          .
---- VAR AIII1102           0.0010       1.2653       +INF          .
---- VAR AIII1103           0.0010       1.1473       +INF          .
---- VAR AIII1104           0.0010       1.0325       +INF          .
---- VAR AIII1105           0.0010       0.9288       +INF          .
---- VAR AIV1101            0.0010       1.5559       +INF          .
---- VAR AIV1102            0.0010       1.5174       +INF          .
---- VAR AIV1103            0.0010       1.4802       +INF          .
---- VAR AIV1104            0.0010       1.4460       +INF          .
---- VAR AIV1105            0.0010       1.4218       +INF          .
---- VAR BLRDT             10.0000     513.2954    1000.0000        .
---- VAR BYPASS             0.0100       0.0878       1.0000        .
---- VAR CI1201             0.0010       1.0774       +INF          .
---- VAR CI1202             0.0010       1.6325       +INF          .
---- VAR CI1203             0.0010       2.4367       +INF          .
---- VAR CI1204             0.0010       3.2234       +INF          .
---- VAR CI1205             0.0010       3.6972       +INF          .
---- VAR CII1201            0.0005       0.8412       +INF          .
---- VAR CII1202            0.0005       1.0088       +INF          .
---- VAR CII1203            0.0005       1.2527       +INF          .
---- VAR CII1204            0.0005       1.5670       +INF          .
---- VAR CII1205            0.0005       1.8190       +INF          .
---- VAR CIII1101           0.0005       0.7868       +INF          .
---- VAR CIII1102           0.0005       0.9000       +INF          .
---- VAR CIII1103           0.0005       1.0406       +INF          .
---- VAR CIII1104           0.0005       1.2165       +INF          .
---- VAR CIII1105           0.0005       1.4230       +INF          .
---- VAR CIV1101            0.0005       0.6625       +INF          .
---- VAR CIV1102            0.0005       0.6876       +INF          .
---- VAR CIV1103            0.0005       0.7134       +INF          .
---- VAR CIV1104            0.0005       0.7385       +INF          .
---- VAR CIV1105            0.0005       0.7572       +INF          .
---- VAR CLRDT             10.0000     319.5859    1000.0000        .
---- VAR CPI1               0.0010       0.0333       +INF          .
---- VAR CPI2               0.0010       0.0340       +INF          .
---- VAR CPI3               0.0010       0.0349       +INF          .
---- VAR CPI4               0.0010       0.0356       +INF          .
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                         LOWER        LEVEL        UPPER       MARGINAL

---- VAR CPI5               0.0010       0.0361       +INF          .
---- VAR CPII1              0.0010       0.0344       +INF          .
---- VAR CPII2              0.0010       0.0347       +INF          .
---- VAR CPII3              0.0010       0.0351       +INF          .
---- VAR CPII4              0.0010       0.0356       +INF          .
---- VAR CPII5              0.0010       0.0359       +INF          .
---- VAR CPIII1             0.0010       0.0312       +INF          .
---- VAR CPIII2             0.0010       0.0313       +INF          .
---- VAR CPIII3             0.0010       0.0314       +INF          .
---- VAR CPIII4             0.0010       0.0315       +INF          .
---- VAR CPIII5             0.0010       0.0317       +INF          .
---- VAR CPIV1              0.0010       0.0313       +INF          .
---- VAR CPIV2              0.0010       0.0314       +INF          .
---- VAR CPIV3              0.0010       0.0314       +INF          .
---- VAR CPIV4              0.0010       0.0314       +INF          .
---- VAR CPIV5              0.0010       0.0314       +INF          .
---- VAR DI1201             0.0010       3.0600       +INF          .
---- VAR DI1202             0.0010       1.6250       +INF          .
---- VAR DI1203             0.0010       0.8831       +INF          .
---- VAR DI1204             0.0010       0.5767       +INF          .
---- VAR DI1205             0.0010       0.4680       +INF          .
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```
---- VAR DII1201        0.0005      4.4605      +INF        .
---- VAR DII1202        0.0005      3.3822      +INF        .
---- VAR DII1203        0.0005      2.4324      +INF        .
---- VAR DII1204        0.0005      1.7297      +INF        .
---- VAR DII1205        0.0005      1.3783      +INF        .
---- VAR DIII1101       0.0005      4.8154      +INF        .
---- VAR DIII1102       0.0005      4.2856      +INF        .
---- VAR DIII1103       0.0005      3.7791      +INF        .
---- VAR DIII1104       0.0005      3.3008      +INF        .
---- VAR DIII1105       0.0005      2.8813      +INF        .
---- VAR DIV1101        0.0005      5.5891      +INF        .
---- VAR DIV1102        0.0005      5.4121      +INF        .
---- VAR DIV1103        0.0005      5.2421      +INF        .
---- VAR DIV1104        0.0005      5.0872      +INF        .
---- VAR DIV1105        0.0005      4.9779      +INF        .
---- VAR DTI1           0.0100     10.4293      +INF        .
---- VAR DTI2           0.0100     13.6547      +INF        .
---- VAR DTI3           0.0100     14.0441      +INF        .
---- VAR DTI4           0.0100      9.7190      +INF        .
---- VAR DTI5           0.0100      4.2510      +INF        .
---- VAR DTII1          0.0100      3.8539      +INF        .
---- VAR DTII2          0.0100      4.8899      +INF        .
---- VAR DTII3          0.0100      6.1221      +INF        .
```

```
                    LOWER       LEVEL       UPPER      MARGINAL

---- VAR DTII4          0.0100      6.4528      +INF        .
---- VAR DTII5          0.0100      3.7358      +INF        .
---- VAR DTIII1         0.0100      1.0369      +INF        .
---- VAR DTIII2         0.0100      1.1555      +INF        .
---- VAR DTIII3         0.0100      1.2692      +INF        .
---- VAR DTIII4         0.0100      1.4029      +INF        .
---- VAR DTIII5         0.0100      1.3898      +INF        .
---- VAR DTIV1          0.0100      0.2407      +INF        .
---- VAR DTIV2          0.0100      0.2433      +INF        .
---- VAR DTIV3          0.0100      0.2404      +INF        .
---- VAR DTIV4          0.0100      0.2201      +INF        .
---- VAR DTIV5          0.0100      0.1304      +INF        .
---- VAR EMISS          0.1000      3.7933      4.0000      .
---- VAR EMISS1         0.0001      0.0038      0.0040      .
---- VAR ENTHI1         0.1000     29.0218      +INF        .
---- VAR ENTHI2         0.1000     32.5247      +INF        .
---- VAR ENTHI3         0.1000     36.6963      +INF        .
---- VAR ENTHI4         0.1000     40.3921      +INF        .
---- VAR ENTHI5         0.1000     42.6183      +INF        .
---- VAR ENTHII1        0.1000     27.5466      +INF        .
---- VAR ENTHII2        0.1000     28.9213      +INF        .
---- VAR ENTHII3        0.1000     30.6812      +INF        .
---- VAR ENTHII4        0.1000     32.7281      +INF        .
---- VAR ENTHII5        0.1000     34.4129      +INF        .
---- VAR ENTHIII1       0.1000     22.5022      +INF        .
---- VAR ENTHIII2       0.1000     23.0247      +INF        .
---- VAR ENTHIII3       0.1000     23.6066      +INF        .
---- VAR ENTHIII4       0.1000     24.2527      +INF        .
---- VAR ENTHIII5       0.1000     24.9333      +INF        .
---- VAR ENTHIV1        0.1000     21.8978      +INF        .
---- VAR ENTHIV2        0.1000     22.0376      +INF        .
---- VAR ENTHIV3        0.1000     22.1776      +INF        .
---- VAR ENTHIV4        0.1000     22.3111      +INF        .
---- VAR ENTHIV5        0.1000     22.4129      +INF        .
---- VAR EX65DT        10.0000    139.6041      +INF        .
---- VAR EX66DT        10.0000    104.1367      +INF        .
---- VAR EX67DT        10.0000    145.9913      +INF        .
---- VAR EX68DT        10.0000    123.7723      +INF        .
---- VAR EX71DT        10.0000    177.9250      +INF        .
---- VAR F06N2          1.2000      1.7441      2.4000      .
---- VAR F06O2          0.0600      0.4636      0.6000      .
---- VAR F07            1.2000      2.2053      2.4000      .
---- VAR F07N2          1.2000      1.7441      1.8000      .
---- VAR F07O2          0.0001      0.2171      0.6000      .
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```
                    LOWER       LEVEL       UPPER      MARGINAL

---- VAR F07SO2         0.0100      0.2392      0.3000      .
---- VAR F07SO3         0.0024      0.0049      0.0072      .
---- VAR F08            0.6000      2.0116      4.0000      .
---- VAR F08A      1.0000000E-5      0.1936      1.2000      .
---- VAR F08AN2    1.0000000E-5      0.1531      0.6000      .
---- VAR F08AO2    1.0000000E-5      0.0191      0.1000      .
---- VAR F08ASO2   1.0000000E-5      0.0210      0.6000      .
---- VAR F08ASO3   1.0000000E-5      0.0004      0.0600      .
---- VAR F08N2          0.3000      1.5910      2.4000      .
---- VAR F08O2          0.0060      0.1981      0.6000      .
---- VAR F08SO2         0.0060      0.2182      0.6000      .
---- VAR F08SO3         0.0006      0.0045      0.0120      .
---- VAR F09            0.6000      2.0116      4.0000      .
```

```
---- VAR F09N2            0.3000        1.5910        4.0000         .
---- VAR F09O2            0.0060        0.1981        0.6000         .
---- VAR F09SO2           0.0060        0.2182        0.6000         .
---- VAR F09SO3           0.0006        0.0045        0.0120         .
---- VAR F10              1.2000        2.2053        2.4000         .
---- VAR F10N2            1.2000        1.7441        1.8000         .
---- VAR F10O2            0.0200        0.2171        0.6000         .
---- VAR F10SO2           0.1800        0.2392        0.3000         .
---- VAR F10SO3           0.0024        0.0049        0.0072         .
---- VAR F11              1.1000        2.1358        2.5000         .
---- VAR F11N2            1.2000        1.7441        1.8000         .
---- VAR F11O2            0.0010        0.1477        0.4000         .
---- VAR F11SO2           0.0100        0.1002        1.0000         .
---- VAR F11SO3           0.0200        0.1438        0.1800         .
---- VAR F12              1.1000        2.1358        2.5000         .
---- VAR F12N2            1.2000        1.7441        1.8000         .
---- VAR F12O2            0.0100        0.1477        0.2200         .
---- VAR F12SO2           0.0100        0.1002        1.0000         .
---- VAR F12SO3           0.0200        0.1438        0.1800         .
---- VAR F13              1.0000        2.1010        3.0000         .
---- VAR F13N2            1.2000        1.7441        1.8000         .
---- VAR F13O2            0.0100        0.1128        0.2000         .
---- VAR F13SO2           0.0050        0.0305        1.0000         .
---- VAR F13SO3           0.0500        0.2135        0.5000         .
---- VAR F14              1.0000        2.1010        3.0000         .
---- VAR F14N2            1.2000        1.7441        1.8000         .
---- VAR F14O2            0.0100        0.1128        0.2000         .
---- VAR F14SO2           0.0050        0.0305        1.0000         .
---- VAR F14SO3           0.0500        0.2135        0.5000         .
---- VAR F15              1.0000        2.1010        3.0000         .
---- VAR F15N2            1.2000        1.7441        1.8000         .
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                    LOWER         LEVEL         UPPER        MARGINAL

---- VAR F15O2            0.0100        0.1128        0.2000         .
---- VAR F15SO2           0.0050        0.0305        1.0000         .
---- VAR F15SO3           0.0500        0.2135        0.5000         .
---- VAR F16              1.0000        1.8874        3.0000         .
---- VAR F16N2            1.2000        1.7441        1.8000         .
---- VAR F16O2            0.0100        0.1128        0.2000         .
---- VAR F16SO2           0.0050        0.0305        1.0000         .
---- VAR F19              1.0000        1.8874        3.0000         .
---- VAR F19N2            1.2000        1.7441        1.8000         .
---- VAR F19O2            0.0100        0.1128        0.2000         .
---- VAR F19SO2           0.0050        0.0305        1.0000         .
---- VAR F20              1.0000        1.8874        3.0000         .
---- VAR F20N2            1.2000        1.7441        1.8000         .
---- VAR F20O2            0.0100        0.1128        0.2000         .
---- VAR F20SO2           0.0050        0.0305        1.0000         .
---- VAR F21              1.0000        1.8751        3.0000         .
---- VAR F21N2            1.2000        1.7441        1.8000         .
---- VAR F21O2            0.0010        0.1005        0.2000         .
---- VAR F21SO2           0.0050        0.0059        1.0000         .
---- VAR F21SO3       1.0000000E-5        0.0246        0.1000         .
---- VAR F22              0.5000        1.8751        3.0000         .
---- VAR F22N2            1.2000        1.7441        1.8000         .
---- VAR F22O2            0.0010        0.1005        0.2000         .
---- VAR F22SO2           0.0001        0.0059        1.0000         .
---- VAR F22SO3           0.0001        0.0246        0.1000         .
---- VAR F23              1.0000        1.8725        3.0000         .
---- VAR F235             1.0000        1.8725        3.0000         .
---- VAR F235N2           1.2000        1.7441        1.8000         .
---- VAR F235O2           0.0010        0.0979        0.2000         .
---- VAR F235SO2          0.0001        0.0007        1.0000         .
---- VAR F235SO3          0.0100        0.0298        0.1000         .
---- VAR F23N2            1.2000        1.7441        1.8000         .
---- VAR F23O2            0.0010        0.0979        0.2000         .
---- VAR F23SO2           0.0001        0.0007        1.0000         .
---- VAR F23SO3           0.0100        0.0298        0.1000         .
---- VAR F24              1.0000        1.8725        3.0000         .
---- VAR F24N2            1.2000        1.7441        1.8000         .
---- VAR F24O2            0.0050        0.0979        0.2000         .
---- VAR F24SO2           0.0001        0.0007        1.0000         .
---- VAR F24SO3           0.0100        0.0298        0.1000         .
---- VAR F25              1.0000        1.8427        3.0000         .
---- VAR F25N2            1.2000        1.7441        1.8000         .
---- VAR F25O2            0.0050        0.0979        0.2000         .
---- VAR F25SO2       1.0000000E-5        0.0007        1.0000         .
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                    LOWER         LEVEL         UPPER        MARGINAL

---- VAR FDW              0.0001        0.3650        +INF           .
---- VAR FFIIISO21         -INF        -0.0094          .            .
---- VAR FFIIISO22         -INF        -0.0105          .            .
---- VAR FFIIISO23         -INF        -0.0117          .            .
---- VAR FFIIISO24         -INF        -0.0123          .            .
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---- VAR FFIISO21          -INF          -0.0266          .             .
---- VAR FFIISO22          -INF          -0.0341          .             .
---- VAR FFIISO23          -INF          -0.0398          .             .
---- VAR FFIISO24          -INF          -0.0328          .             .
---- VAR FFISO21           -INF          -0.0753          .             .
---- VAR FFISO22           -INF          -0.0901          .             .
---- VAR FFISO23           -INF          -0.0802          .             .
---- VAR FFISO24           -INF          -0.0485          .             .
---- VAR FFIVSO21          -INF          -0.0021          .             .
---- VAR FFIVSO22          -INF          -0.0021          .             .
---- VAR FFIVSO23          -INF          -0.0020          .             .
---- VAR FFIVSO24          -INF          -0.0015          .             .
---- VAR FFPROD            0.0001         0.6084        +INF            .
---- VAR FIIIO21           0.0010         0.1128        +INF            .
---- VAR FIIIO22           0.0010         0.1102        +INF            .
---- VAR FIIIO23           0.0010         0.1072        +INF            .
---- VAR FIIIO24           0.0010         0.1040        +INF            .
---- VAR FIIIO25           0.0010         0.1005        +INF            .
---- VAR FIIISO21          0.0001         0.0305        +INF            .
---- VAR FIIISO22          0.0001         0.0252        +INF            .
---- VAR FIIISO23          0.0001         0.0194        +INF            .
---- VAR FIIISO24          0.0001         0.0128        +INF            .
---- VAR FIIISO25          0.0001         0.0059        +INF            .
---- VAR FIIISO31            .              .           +INF            .
---- VAR FIIISO32          0.0010         0.0053        +INF            .
---- VAR FIIISO33          0.0010         0.0112        +INF            .
---- VAR FIIISO34          0.0010         0.0177        +INF            .
---- VAR FIIISO35          0.0010         0.0246        +INF            .
---- VAR FIIO21            0.0010         0.1477        +INF            .
---- VAR FIIO22            0.0010         0.1407        +INF            .
---- VAR FIIO23            0.0010         0.1318        +INF            .
---- VAR FIIO24            0.0010         0.1214        +INF            .
---- VAR FIIO25            0.0010         0.1128        +INF            .
---- VAR FIISO21           0.0010         0.1002        +INF            .
---- VAR FIISO22           0.0010         0.0863        +INF            .
---- VAR FIISO23           0.0010         0.0685        +INF            .
---- VAR FIISO24           0.0010         0.0477        +INF            .
---- VAR FIISO25           0.0010         0.0305        +INF            .
---- VAR FIISO31           0.0010         0.1438        +INF            .
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                          LOWER          LEVEL          UPPER         MARGINAL

---- VAR FIISO32           0.0010         0.1577        +INF            .
---- VAR FIISO33           0.0010         0.1756        +INF            .
---- VAR FIISO34           0.0010         0.1964        +INF            .
---- VAR FIISO35           0.0010         0.2135        +INF            .
---- VAR FIO21             0.0010         0.2171        +INF            .
---- VAR FIO22             0.0010         0.1993        +INF            .
---- VAR FIO23             0.0010         0.1781        +INF            .
---- VAR FIO24             0.0010         0.1591        +INF            .
---- VAR FIO25             0.0010         0.1477        +INF            .
---- VAR FISO21            0.0010         0.2392        +INF            .
---- VAR FISO22            0.0010         0.2036        +INF            .
---- VAR FISO23            0.0010         0.1610        +INF            .
---- VAR FISO24            0.0010         0.1231        +INF            .
---- VAR FISO25            0.0010         0.1002        +INF            .
---- VAR FISO31              .            0.0049        +INF            .
---- VAR FISO32              .            0.0405        +INF            .
---- VAR FISO33              .            0.0830        +INF            .
---- VAR FISO34              .            0.1209        +INF            .
---- VAR FISO35            0.0010         0.1438        +INF            .
---- VAR FIVO21            0.0010         0.1005        +INF            .
---- VAR FIVO22            0.0010         0.0998        +INF            .
---- VAR FIVO23            0.0010         0.0991        +INF            .
---- VAR FIVO24            0.0010         0.0984        +INF            .
---- VAR FIVO25            0.0010         0.0979        +INF            .
---- VAR FIVSO21           0.0001         0.0059        +INF            .
---- VAR FIVSO22           0.0001         0.0045        +INF            .
---- VAR FIVSO23           0.0001         0.0031        +INF            .
---- VAR FIVSO24           0.0001         0.0017        +INF            .
---- VAR FIVSO25           0.0001         0.0007        +INF            .
---- VAR FIVSO31             .            0.0246        +INF            .
---- VAR FIVSO32             .            0.0260        +INF            .
---- VAR FIVSO33             .            0.0274        +INF            .
---- VAR FIVSO34             .            0.0288        +INF            .
---- VAR FIVSO35             .            0.0298        +INF            .
---- VAR FPROD             0.0001        26.0384        +INF            .
---- VAR FSBD              0.1000         0.1950        +INF            .
---- VAR FSHP1             0.1000         1.2200        +INF            .
---- VAR FSHP2             0.1000         0.5350        +INF            .
---- VAR FSS1              0.1000         1.9500        +INF            .
---- VAR FSS1A             0.1000         1.4795        +INF            .
---- VAR FSS1B             0.1000         0.4705        +INF            .
---- VAR FSS2              0.1000         1.7550        +INF            .
---- VAR FSS4              0.1000         1.2200        +INF            .
---- VAR FSS5              0.1000         0.5350        +INF            .
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```

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                      LOWER          LEVEL          UPPER         MARGINAL

---- VAR FSW1               0.1000          1.9500         +INF             .
---- VAR FSW1A              0.1000          1.4795         +INF             .
---- VAR FSW1B              0.1000          0.4705         +INF             .
---- VAR FTRIIIN21          -INF            3.1494         +INF             .
---- VAR FTRIIIN22          -INF            3.1762         +INF             .
---- VAR FTRIIIN23          -INF            3.2058         +INF             .
---- VAR FTRIIIN24          -INF            3.2383         +INF             .
---- VAR FTRIIIN25          -INF            3.2723         +INF             .
---- VAR FTRIIIO21          -INF            2.7463         +INF             .
---- VAR FTRIIIO22          -INF            2.7701         +INF             .
---- VAR FTRIIIO23          -INF            2.7963         +INF             .
---- VAR FTRIIIO24          -INF            2.8253         +INF             .
---- VAR FTRIIIO25          -INF            2.8554         +INF             .
---- VAR FTRIIISO21         -INF            1.2816         +INF             .
---- VAR FTRIIISO22         -INF            1.2952         +INF             .
---- VAR FTRIIISO23         -INF            1.3102         +INF             .
---- VAR FTRIIISO24         -INF            1.3267         +INF             .
---- VAR FTRIIISO25         -INF            1.3439         +INF             .
---- VAR FTRIIISO31         -INF            1.1448         +INF             .
---- VAR FTRIIISO32         -INF            1.1574         +INF             .
---- VAR FTRIIISO33         -INF            1.1713         +INF             .
---- VAR FTRIIISO34         -INF            1.1867         +INF             .
---- VAR FTRIIISO35         -INF            1.2026         +INF             .
---- VAR FTRIIN21           -INF            3.1410         +INF             .
---- VAR FTRIIN22           -INF            3.1971         +INF             .
---- VAR FTRIIN23           -INF            3.2677         +INF             .
---- VAR FTRIIN24           -INF            3.3480         +INF             .
---- VAR FTRIIN25           -INF            3.4127         +INF             .
---- VAR FTRIIO21           -INF            2.7388         +INF             .
---- VAR FTRIIO22           -INF            2.7887         +INF             .
---- VAR FTRIIO23           -INF            2.8513         +INF             .
---- VAR FTRIIO24           -INF            2.9226         +INF             .
---- VAR FTRIIO25           -INF            2.9800         +INF             .
---- VAR FTRIISO21          -INF            1.2773         +INF             .
---- VAR FTRIISO22          -INF            1.3058         +INF             .
---- VAR FTRIISO23          -INF            1.3416         +INF             .
---- VAR FTRIISO24          -INF            1.3822         +INF             .
---- VAR FTRIISO25          -INF            1.4150         +INF             .
---- VAR FTRIISO31          -INF            1.1408         +INF             .
---- VAR FTRIISO32          -INF            1.1673         +INF             .
---- VAR FTRIISO33          -INF            1.2005         +INF             .
---- VAR FTRIISO34          -INF            1.2382         +INF             .
---- VAR FTRIISO35          -INF            1.2686         +INF             .
---- VAR FTRIN21            -INF            3.2027         +INF             .
```

```
                      LOWER          LEVEL          UPPER         MARGINAL

---- VAR FTRIN22            -INF            3.3424         +INF             .
---- VAR FTRIN23            -INF            3.5019         +INF             .
---- VAR FTRIN24            -INF            3.6375         +INF             .
---- VAR FTRIN25            -INF            3.7169         +INF             .
---- VAR FTRIO21            -INF            2.7936         +INF             .
---- VAR FTRIO22            -INF            2.9176         +INF             .
---- VAR FTRIO23            -INF            3.0590         +INF             .
---- VAR FTRIO24            -INF            3.1792         +INF             .
---- VAR FTRIO25            -INF            3.2494         +INF             .
---- VAR FTRISO21           -INF            1.3086         +INF             .
---- VAR FTRISO22           -INF            1.3794         +INF             .
---- VAR FTRISO23           -INF            1.4600         +INF             .
---- VAR FTRISO24           -INF            1.5282         +INF             .
---- VAR FTRISO25           -INF            1.5680         +INF             .
---- VAR FTRISO31           -INF            1.1699         +INF             .
---- VAR FTRISO32           -INF            1.2356         +INF             .
---- VAR FTRISO33           -INF            1.3104         +INF             .
---- VAR FTRISO34           -INF            1.3739         +INF             .
---- VAR FTRISO35           -INF            1.4109         +INF             .
---- VAR FTRIVN21           -INF            3.1179         +INF             .
---- VAR FTRIVN22           -INF            3.1252         +INF             .
---- VAR FTRIVN23           -INF            3.1324         +INF             .
---- VAR FTRIVN24           -INF            3.1393         +INF             .
---- VAR FTRIVN25           -INF            3.1445         +INF             .
---- VAR FTRIVO21           -INF            2.7183         +INF             .
---- VAR FTRIVO22           -INF            2.7247         +INF             .
---- VAR FTRIVO23           -INF            2.7312         +INF             .
---- VAR FTRIVO24           -INF            2.7373         +INF             .
---- VAR FTRIVO25           -INF            2.7419         +INF             .
---- VAR FTRIVSO21          -INF            1.2656         +INF             .
---- VAR FTRIVSO22          -INF            1.2693         +INF             .
---- VAR FTRIVSO23          -INF            1.2729         +INF             .
---- VAR FTRIVSO24          -INF            1.2764         +INF             .
---- VAR FTRIVSO25          -INF            1.2791         +INF             .
---- VAR FTRIVSO31          -INF            1.1300         +INF             .
---- VAR FTRIVSO32          -INF            1.1334         +INF             .
---- VAR FTRIVSO33          -INF            1.1368         +INF             .
---- VAR FTRIVSO34          -INF            1.1401         +INF             .
---- VAR FTRIVSO35          -INF            1.1425         +INF             .
```

```
---- VAR H06               0.0100         3.6691        +INF            .
---- VAR H07               0.0100        76.5040        +INF            .
---- VAR H08               0.0100        69.7862        +INF            .
---- VAR H08A              0.0100         6.7177        +INF            .
---- VAR H09               0.0100        22.3040        +INF            .
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                        LOWER         LEVEL         UPPER        MARGINAL

---- VAR H10               0.0100        29.0218        +INF            .
---- VAR H11               0.0100        42.6183        +INF            .
---- VAR H12               0.0100        27.5466        +INF            .
---- VAR H13               0.0100        34.4129        +INF            .
---- VAR H14               0.0100        25.7384        +INF            .
---- VAR H15               0.0100        14.0911        +INF            .
---- VAR H16               0.0100         2.5955        +INF            .
---- VAR H19               0.0100        14.0087        +INF            .
---- VAR H20               0.0100        22.5022        +INF            .
---- VAR H21               0.0100        24.9333        +INF            .
---- VAR H22               0.0100        21.8978        +INF            .
---- VAR H23               0.0100        22.4129        +INF            .
---- VAR H235              0.0100        21.3040        +INF            .
---- VAR H24               0.0100        11.6485        +INF            .
---- VAR H25               0.0100         2.8103        +INF            .
---- VAR H50               0.0100         0.9947        +INF            .
---- VAR HRSO2           200.0000       314.0424      500.0000          .
---- VAR HRSO3            30.0000        90.8323      150.0000          .
---- VAR HSBD              0.0100         3.4474        +INF            .
---- VAR HSBFW             0.0100        16.0529        +INF            .
---- VAR HSHP1             0.0100        67.8278        +INF            .
---- VAR HSHP2             0.0100        29.5363        +INF            .
---- VAR HSS1              0.0100        86.7847        +INF            .
---- VAR HSS1A             0.0100        65.8455        +INF            .
---- VAR HSS1B             0.0100        20.9392        +INF            .
---- VAR HSS2              0.0100        93.2956        +INF            .
---- VAR HSS4              0.0100        64.8541        +INF            .
---- VAR HSS5              0.0100        28.4415        +INF            .
---- VAR HSW1              0.0100        25.4997        +INF            .
---- VAR HSW1A             0.0100        19.3472        +INF            .
---- VAR HSW1B             0.0100         6.1525        +INF            .
---- VAR JHI1              0.0010         0.1166        +INF            .
---- VAR JHI2              0.0010         0.1192        +INF            .
---- VAR JHI3              0.0010         0.1221        +INF            .
---- VAR JHI4              0.0010         0.1245        +INF            .
---- VAR JHI5              0.0010         0.1259        +INF            .
---- VAR JHII1             0.0010         0.1152        +INF            .
---- VAR JHII2             0.0010         0.1163        +INF            .
---- VAR JHII3             0.0010         0.1176        +INF            .
---- VAR JHII4             0.0010         0.1191        +INF            .
---- VAR JHII5             0.0010         0.1203        +INF            .
---- VAR JHIII1            0.0010         0.1538        +INF            .
---- VAR JHIII2            0.0010         0.1544        +INF            .
---- VAR JHIII3            0.0010         0.1552        +INF            .
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                        LOWER         LEVEL         UPPER        MARGINAL

---- VAR JHIII4            0.0010         0.1560        +INF            .
---- VAR JHIII5            0.0010         0.1568        +INF            .
---- VAR JHIV1             0.0010         0.1530        +INF            .
---- VAR JHIV2             0.0010         0.1531        +INF            .
---- VAR JHIV3             0.0010         0.1533        +INF            .
---- VAR JHIV4             0.0010         0.1535        +INF            .
---- VAR JHIV5             0.0010         0.1536        +INF            .
---- VAR KPI1              0.1000       167.5790        +INF            .
---- VAR KPI2              0.1000        57.7866        +INF            .
---- VAR KPI3              0.1000        20.7122        +INF            .
---- VAR KPI4              0.1000        10.1142        +INF            .
---- VAR KPI5              0.1000         7.1179        +INF            .
---- VAR KPII1             0.1000       315.9068        +INF            .
---- VAR KPII2             0.1000       198.3198        +INF            .
---- VAR KPII3             0.1000       113.8974        +INF            .
---- VAR KPII4             0.1000        64.1865        +INF            .
---- VAR KPII5             0.1000        43.8053        +INF            .
---- VAR KPIII1            0.1000       316.1271        +INF            .
---- VAR KPIII2            0.1000       254.6963        +INF            .
---- VAR KPIII3            0.1000       201.7206        +INF            .
---- VAR KPIII4            0.1000       156.9617        +INF            .
---- VAR KPIII5            0.1000       121.9951        +INF            .
---- VAR KPIV1             0.1000       416.7150        +INF            .
---- VAR KPIV2             0.1000       392.5728        +INF            .
---- VAR KPIV3             0.1000       370.0183        +INF            .
---- VAR KPIV4             0.1000       350.0124        +INF            .
---- VAR KPIV5             0.1000       336.1954        +INF            .
---- VAR MFI1             15.0000       500.1367        +INF            .
---- VAR MFI2             15.0000       500.1367        +INF            .
---- VAR MFI3             15.0000       500.1367        +INF            .
---- VAR MFI4             15.0000       500.1367        +INF            .
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---- VAR MFI5          15.0000     500.1367      +INF          .
---- VAR MFII1         15.5290     500.1367      +INF          .
---- VAR MFII2         15.5290     500.1367      +INF          .
---- VAR MFII3         15.5290     500.1367      +INF          .
---- VAR MFII4         15.5290     500.1367      +INF          .
---- VAR MFII5         15.5290     500.1367      +INF          .
---- VAR MFIII1        15.2290     380.6179      +INF          .
---- VAR MFIII2        15.2290     380.6179      +INF          .
---- VAR MFIII3        15.2290     380.6179      +INF          .
---- VAR MFIII4        15.2290     380.6179      +INF          .
---- VAR MFIII5        15.2290     380.6179      +INF          .
---- VAR MFIV1         15.1120     380.6179      +INF          .
---- VAR MFIV2         15.1120     380.6179      +INF          .
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                        LOWER        LEVEL        UPPER       MARGINAL

---- VAR MFIV3         15.1120     380.6179      +INF          .
---- VAR MFIV4         15.1120     380.6179      +INF          .
---- VAR MFIV5         15.1120     380.6179      +INF          .
---- VAR MWPROD          40.0000      42.8000      45.0000          .
---- VAR PROFIT           .           0.3077      +INF          .
---- VAR PSBD         600.0000     712.5188     900.0000          .
---- VAR PSS1         600.0000     712.5188     900.0000          .
---- VAR PSS1A        600.0000     712.5188     900.0000          .
---- VAR PSS1B        600.0000     712.5188     900.0000   3.5543883E-7
---- VAR PSS4         600.0000     712.5188     900.0000          .
---- VAR PSS5         600.0000     712.5188     900.0000          .
---- VAR RATEI1         -INF          0.0117      +INF          .
---- VAR RATEI2         -INF          0.0160      +INF          .
---- VAR RATEI3         -INF          0.0172      +INF          .
---- VAR RATEI4         -INF          0.0123      +INF          .
---- VAR RATEI5         -INF          0.0055      +INF          .
---- VAR RATEII1        -INF          0.0043      +INF          .
---- VAR RATEII2        -INF          0.0055      +INF          .
---- VAR RATEII3        -INF          0.0070      +INF          .
---- VAR RATEII4        -INF          0.0076      +INF          .
---- VAR RATEII5        -INF          0.0045      +INF          .
---- VAR RATEIII1       -INF          0.0018      +INF          .
---- VAR RATEIII2       -INF          0.0021      +INF          .
---- VAR RATEIII3       -INF          0.0023      +INF          .
---- VAR RATEIII4       -INF          0.0026      +INF          .
---- VAR RATEIII5       -INF          0.0026      +INF          .
---- VAR RATEINIII1       0.0005       0.0217      +INF          .
---- VAR RATEINIII2       0.0005       0.0243      +INF          .
---- VAR RATEINIII3       0.0005       0.0269      +INF          .
---- VAR RATEINIII4       0.0005       0.0300      +INF          .
---- VAR RATEINIII5       0.0005       0.0300      +INF          .
---- VAR RATEINTI1        0.0005       0.0462      +INF          .
---- VAR RATEINTI2        0.0005       0.0629      +INF          .
---- VAR RATEINTI3        0.0005       0.0676      +INF          .
---- VAR RATEINTI4        0.0005       0.0485      +INF          .
---- VAR RATEINTI5        0.0005       0.0217      +INF          .
---- VAR RATEINTII1       0.0050       0.0179      +INF          .
---- VAR RATEINTII2       0.0050       0.0231      +INF          .
---- VAR RATEINTII3       0.0050       0.0295      +INF          .
---- VAR RATEINTII4       0.0050       0.0318      +INF          .
---- VAR RATEINTII5       0.0050       0.0187      +INF          .
---- VAR RATEINTIV1       0.0005       0.0127      +INF          .
---- VAR RATEINTIV2       0.0005       0.0128      +INF          .
---- VAR RATEINTIV3       0.0005       0.0127      +INF          .
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                        LOWER        LEVEL        UPPER       MARGINAL

---- VAR RATEINTIV4       0.0005       0.0117      +INF          .
---- VAR RATEINTIV5       0.0005       0.0069      +INF          .
---- VAR RATEIV1        -INF          0.0004      +INF          .
---- VAR RATEIV2        -INF          0.0004      +INF          .
---- VAR RATEIV3        -INF          0.0004      +INF          .
---- VAR RATEIV4        -INF          0.0004      +INF          .
---- VAR RATEIV5        -INF          0.0002      +INF          .
---- VAR RHEATI1          0.1000      44.7060      +INF          .
---- VAR RHEATI2          0.1000      44.5115      +INF          .
---- VAR RHEATI3          0.1000      44.2736      +INF          .
---- VAR RHEATI4          0.1000      44.0695      +INF          .
---- VAR RHEATI5          0.1000      43.9555      +INF          .
---- VAR RHEATII1         1.0000      44.8018      +INF          .
---- VAR RHEATII2         1.0000      44.7327      +INF          .
---- VAR RHEATII3         1.0000      44.6407      +INF          .
---- VAR RHEATII4         1.0000      44.5328      +INF          .
---- VAR RHEATII5         1.0000      44.4527      +INF          .
---- VAR RHEATIII1        0.1000      44.8019      +INF          .
---- VAR RHEATIII2        0.1000      44.7707      +INF          .
---- VAR RHEATIII3        0.1000      44.7354      +INF          .
---- VAR RHEATIII4        0.1000      44.6953      +INF          .
---- VAR RHEATIII5        0.1000      44.6527      +INF          .
---- VAR RHEATIV1         1.0000      44.8397      +INF          .
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---- VAR RHEATIV2         1.0000      44.8317        +INF          .
---- VAR RHEATIV3         1.0000      44.8237        +INF          .
---- VAR RHEATIV4         1.0000      44.8161        +INF          .
---- VAR RHEATIV5         1.0000      44.8105        +INF          .
---- VAR SO2PPM1          0.1000       0.3800       0.3800         .
---- VAR T08           1000.0000    1321.8456    1500.0000         .
---- VAR T08A          1000.0000    1321.8456    1500.0000         .
---- VAR T14            500.0000     667.4509     800.0000         .
---- VAR TCATI1         580.0100     723.0849        +INF          .
---- VAR TCATI2         625.2600     773.5083        +INF          .
---- VAR TCATI3         670.5100     829.2340        +INF          .
---- VAR TCATI4         715.7600     873.1800        +INF          .
---- VAR TCATI5         761.0100     896.4660        +INF          .
---- VAR TCATII1        606.0100     696.0655        +INF          .
---- VAR TCATII2        625.2600     715.7044        +INF          .
---- VAR TCATII3        644.5100     740.5949        +INF          .
---- VAR TCATII4        663.7600     768.2234        +INF          .
---- VAR TCATII5        683.0100     787.8011        +INF          .
---- VAR TCATIII1       601.8270     696.0369        +INF          .
---- VAR TCATIII2       609.3730     705.0150        +INF          .
---- VAR TCATIII3       616.9180     714.9677        +INF          .
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                      LOWER        LEVEL        UPPER       MARGINAL

---- VAR TCATIII4       624.4640     725.9943        +INF          .
---- VAR TCATIII5       632.0100     737.4188        +INF          .
---- VAR TCATIV1        588.0100     684.8859        +INF          .
---- VAR TCATIV2        594.2600     687.2645        +INF          .
---- VAR TCATIV3        600.5100     689.6391        +INF          .
---- VAR TCATIV4        606.7600     691.8848        +INF          .
---- VAR TCATIV5        613.0100     693.5212        +INF          .
---- VAR TFI1             0.0010       2.2053        +INF          .
---- VAR TFI2             0.0010       2.1875        +INF          .
---- VAR TFI3             0.0010       2.1662        +INF          .
---- VAR TFI4             0.0010       2.1473        +INF          .
---- VAR TFI5             0.0010       2.1358        +INF          .
---- VAR TFII1            0.1030       2.1358        +INF          .
---- VAR TFII2            0.1030       2.1289        +INF          .
---- VAR TFII3            0.1030       2.1199        +INF          .
---- VAR TFII4            0.1030       2.1095        +INF          .
---- VAR TFII5            0.1030       2.1010        +INF          .
---- VAR TFIII1           0.1020       1.8874        +INF          .
---- VAR TFIII2           0.1020       1.8848        +INF          .
---- VAR TFIII3           0.1020       1.8819        +INF          .
---- VAR TFIII4           0.1020       1.8786        +INF          .
---- VAR TFIII5           0.1020       1.8751        +INF          .
---- VAR TFIV1            0.1020       1.8751        +INF          .
---- VAR TFIV2            0.1020       1.8744        +INF          .
---- VAR TFIV3            0.1020       1.8737        +INF          .
---- VAR TFIV4            0.1020       1.8730        +INF          .
---- VAR TFIV5            0.1020       1.8725        +INF          .
---- VAR TGASI1         580.0000     712.6556     797.0000         .
---- VAR TGASI2         625.2500     759.8536     842.2500         .
---- VAR TGASI3         670.5000     815.1899     887.5000         .
---- VAR TGASI4         715.7500     863.4611     932.7500         .
---- VAR TGASI5         761.0000     892.2150     978.0000         .
---- VAR TGASII1        606.0000     692.2116     823.0000         .
---- VAR TGASII2        625.2500     710.8146     842.2500         .
---- VAR TGASII3        644.5000     734.4728     861.5000         .
---- VAR TGASII4        663.7500     761.7706     880.7500         .
---- VAR TGASII5        683.0000     784.0652     900.0000         .
---- VAR TGASIII1       601.8170     695.0000     818.0000         .
---- VAR TGASIII2       609.3630     703.8595     825.7500         .
---- VAR TGASIII3       616.9080     713.6986     833.5000         .
---- VAR TGASIII4       624.4540     724.5914     841.2500         .
---- VAR TGASIII5       632.0000     736.0289     849.0000         .
---- VAR TGASIV1        588.0000     684.6452     805.0000         .
---- VAR TGASIV2        594.2500     687.0212     811.2500         .
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                      LOWER        LEVEL        UPPER       MARGINAL

---- VAR TGASIV3        600.5000     689.3987     817.5000         .
---- VAR TGASIV4        606.7500     691.6647     823.7500         .
---- VAR TGASIV5        613.0000     693.3908     830.0000         .
---- VAR THHI1            0.0100       7.4136        +INF          .
---- VAR THHI2            0.0100       8.8287        +INF          .
---- VAR THHI3            0.0100       7.8218        +INF          .
---- VAR THHI4            0.0100       4.7117        +INF          .
---- VAR THHII1           0.0100       2.6309        +INF          .
---- VAR THHII2           0.0100       3.3682        +INF          .
---- VAR THHII3           0.0100       3.9176        +INF          .
---- VAR THHII4           0.0100       3.2245        +INF          .
---- VAR THHIII1          0.0100       0.9330        +INF          .
---- VAR THHIII2          0.0100       1.0390        +INF          .
---- VAR THHIII3          0.0100       1.1538        +INF          .
---- VAR THHIII4          0.0100       1.2154        +INF          .
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---- VAR THHIV1           0.0100       0.2041      +INF          .
---- VAR THHIV2           0.0100       0.2043      +INF          .
---- VAR THHIV3           0.0100       0.1949      +INF          .
---- VAR THHIV4           0.0100       0.1485      +INF          .
---- VAR TRIIIN21         4.7690       5.5071       6.4820       .
---- VAR TRIIIN22         4.8290       5.5773       6.5430       .
---- VAR TRIIIN23         4.8880       5.6553       6.6050       .
---- VAR TRIIIN24         4.9480       5.7416       6.6660       .
---- VAR TRIIIN25         5.0080       5.8322       6.7270       .
---- VAR TRIIIO21         3.8930       4.4955       5.2910       .
---- VAR TRIIIO22         3.9420       4.5528       5.3410       .
---- VAR TRIIIO23         3.9900       4.6164       5.3910       .
---- VAR TRIIIO24         4.0390       4.6869       5.4410       .
---- VAR TRIIIO25         4.0880       4.7609       5.4920       .
---- VAR TRIIISO21         1.3980       1.6149       1.9010       .
---- VAR TRIIISO22         1.4160       1.6355       1.9190       .
---- VAR TRIIISO23         1.4330       1.6584       1.9370       .
---- VAR TRIIISO24         1.4510       1.6837       1.9550       .
---- VAR TRIIISO25         1.4690       1.7103       1.9730       .
---- VAR TRIIISO31         1.2250       1.4142       1.6640       .
---- VAR TRIIISO32         1.2400       1.4322       1.6800       .
---- VAR TRIIISO33         1.2550       1.4522       1.6960       .
---- VAR TRIIISO34         1.2710       1.4744       1.7120       .
---- VAR TRIIISO35         1.2860       1.4976       1.7280       .
---- VAR TRIIN21         4.8020       5.4850       6.5210       .
---- VAR TRIIN22         4.9540       5.6324       6.6740       .
---- VAR TRIIN23         5.1070       5.8199       6.8260       .
---- VAR TRIIN24         5.2600       6.0362       6.9790       .
---- VAR TRIIN25         5.4120       6.2129       7.1320       .
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                       LOWER         LEVEL         UPPER        MARGINAL

---- VAR TRIIO21          3.9200       4.4774       5.3230       .
---- VAR TRIIO22          4.0440       4.5978       5.4480       .
---- VAR TRIIO23          4.1690       4.7508       5.5720       .
---- VAR TRIIO24          4.2930       4.9274       5.6970       .
---- VAR TRIIO25          4.4180       5.0716       5.8210       .
---- VAR TRIISO21          1.4080       1.6084       1.9120       .
---- VAR TRIISO22          1.4530       1.6517       1.9570       .
---- VAR TRIISO23          1.4980       1.7066       2.0020       .
---- VAR TRIISO24          1.5420       1.7701       2.0470       .
---- VAR TRIISO25          1.5870       1.8219       2.0910       .
---- VAR TRIISO31          1.2330       1.4085       1.6750       .
---- VAR TRIISO32          1.2720       1.4463       1.7140       .
---- VAR TRIISO33          1.3110       1.4945       1.7530       .
---- VAR TRIISO34          1.3510       1.5500       1.7920       .
---- VAR TRIISO35          1.3900       1.5954       1.8310       .
---- VAR TRIN21          4.5960       5.6470       6.3150       .
---- VAR TRIN22          4.9540       6.0210       6.6740       .
---- VAR TRIN23          5.3130       6.4595       7.0320       .
---- VAR TRIN24          5.6720       6.8420       7.3910       .
---- VAR TRIN25          6.0300       7.0698       7.7500       .
---- VAR TRIO21          3.7520       4.6097       5.1550       .
---- VAR TRIO22          4.0440       4.9150       5.4480       .
---- VAR TRIO23          4.3370       5.2729       5.7410       .
---- VAR TRIO24          4.6300       5.5851       6.0330       .
---- VAR TRIO25          4.9220       5.7711       6.3260       .
---- VAR TRISO21          1.3480       1.6560       1.8520       .
---- VAR TRISO22          1.4530       1.7656       1.9570       .
---- VAR TRISO23          1.5580       1.8942       2.0620       .
---- VAR TRISO24          1.6630       2.0064       2.1670       .
---- VAR TRISO25          1.7680       2.0732       2.2730       .
---- VAR TRISO31          1.1800       1.4501       1.6220       .
---- VAR TRISO32          1.2720       1.5461       1.7140       .
---- VAR TRISO33          1.3640       1.6587       1.8060       .
---- VAR TRISO34          1.4560       1.7569       1.8980       .
---- VAR TRISO35          1.5480       1.8154       1.9900       .
---- VAR TRIVN21          4.6590       5.4251       6.3790       .
---- VAR TRIVN22          4.7090       5.4439       6.4280       .
---- VAR TRIVN23          4.7580       5.4627       6.4780       .
---- VAR TRIVN24          4.8080       5.4807       6.5270       .
---- VAR TRIVN25          4.8570       5.4944       6.5770       .
---- VAR TRIVO21           3.8030       4.4285       5.2070       .
---- VAR TRIVO22           3.8440       4.4439       5.2470       .
---- VAR TRIVO23           3.8840       4.4592       5.2880       .
---- VAR TRIVO24           3.9250       4.4739       5.3280       .
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                       LOWER         LEVEL         UPPER        MARGINAL

---- VAR TRIVO25           3.9650       4.4851       5.3690       .
---- VAR TRIVSO21           1.3660       1.5909       1.8710       .
---- VAR TRIVSO22           1.3810       1.5964       1.8850       .
---- VAR TRIVSO23           1.3950       1.6019       1.9000       .
---- VAR TRIVSO24           1.4100       1.6072       1.9140       .
---- VAR TRIVSO25           1.4240       1.6112       1.9290       .
---- VAR TRIVSO31           1.1960       1.3931       1.6380       .
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---- VAR TRIVSO32          1.2090        1.3979        1.6510          .
---- VAR TRIVSO33          1.2220        1.4028        1.6630          .
---- VAR TRIVSO34          1.2350        1.4074        1.6760          .
---- VAR TRIVSO35          1.2470        1.4109        1.6890          .
---- VAR TSBD            100.0000      442.2992      700.0000          .
---- VAR TSS1            100.0000      442.2992      700.0000          .
---- VAR TSS1A           100.0000      442.2992      700.0000          .
---- VAR TSS1B           100.0000      442.2992      700.0000          .
---- VAR TSS2            100.0000      442.2992      700.0000          .
---- VAR TSS4            100.0000      442.2992      700.0000          .
---- VAR TSS5            100.0000      442.2992      700.0000          .
---- VAR TSW1A           100.0000      339.8194      700.0000          .
---- VAR TSW1B           100.0000      339.8194      700.0000          .
---- VAR VISCI1            0.0010        0.1430        +INF            .
---- VAR VISCI2            0.0010        0.1493        +INF            .
---- VAR VISCI3            0.0010        0.1565        +INF            .
---- VAR VISCI4            0.0010        0.1626        +INF            .
---- VAR VISCI5            0.0010        0.1662        +INF            .
---- VAR VISCII1           0.0010        0.1398        +INF            .
---- VAR VISCII2           0.0010        0.1423        +INF            .
---- VAR VISCII3           0.0010        0.1455        +INF            .
---- VAR VISCII4           0.0010        0.1492        +INF            .
---- VAR VISCII5           0.0010        0.1521        +INF            .
---- VAR VISCIII1          0.0010        0.1407        +INF            .
---- VAR VISCIII2          0.0010        0.1419        +INF            .
---- VAR VISCIII3          0.0010        0.1432        +INF            .
---- VAR VISCIII4          0.0010        0.1446        +INF            .
---- VAR VISCIII5          0.0010        0.1461        +INF            .
---- VAR VISCIV1           0.0010        0.1392        +INF            .
---- VAR VISCIV2           0.0010        0.1395        +INF            .
---- VAR VISCIV3           0.0010        0.1398        +INF            .
---- VAR VISCIV4           0.0010        0.1401        +INF            .
---- VAR VISCIV5           0.0010        0.1404        +INF            .
---- VAR WBRATIO           0.0100        0.7587        1.0000          .
---- VAR XPROD             0.4000        0.4000        0.4200        -0.5812

  F06
```

```
  F50
  FSBFW
  O2PERCENT
  PSHP1
  PSHP2
  PSS2
  SO2PPM
  T06
  T07
  T09
  T10
  T11
  T12
  T13
  T15
  T16
  T19
  T20
  T21
  T22
  T23
  T235
  T24
  T25
  TSBFW
  TSHP1
  TSHP2
  TSW1
  OBJVAR      objective or profit function
  AI1201
  AI1202
  AI1203
  AI1204
  AI1205
  AII1201
  AII1202
  AII1203
  AII1204
  AII1205
  AIII1101
  AIII1102
  AIII1103
  AIII1104
  AIII1105
  AIV1101
  AIV1102
```

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  AIV1103
```

```
AIV1104
AIV1105
BLRDT
BYPASS
CI1201
CI1202
CI1203
CI1204
CI1205
CII1201
CII1202
CII1203
CII1204
CII1205
CIII1101
CIII1102
CIII1103
CIII1104
CIII1105
CIV1101
CIV1102
CIV1103
CIV1104
CIV1105
CLRDT
CPI1
CPI2
CPI3
CPI4
CPI5
CPII1
CPII2
CPII3
CPII4
CPII5
CPIII1
CPIII2
CPIII3
CPIII4
CPIII5
CPIV1
CPIV2
CPIV3
CPIV4
CPIV5
```

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DI1201
DI1202
DI1203
DI1204
DI1205
DII1201
DII1202
DII1203
DII1204
DII1205
DIII1101
DIII1102
DIII1103
DIII1104
DIII1105
DIV1101
DIV1102
DIV1103
DIV1104
DIV1105
DTI1
DTI2
DTI3
DTI4
DTI5
DTII1
DTII2
DTII3
DTII4
DTII5
DTIII1
DTIII2
DTIII3
DTIII4
DTIII5
DTIV1
DTIV2
DTIV3
DTIV4
DTIV5
EMISS
EMISS1
ENTHI1
```

```
  ENTHI2
  ENTHI3
  ENTHI4
```

```
  ENTHI5
  ENTHII1
  ENTHII2
  ENTHII3
  ENTHII4
  ENTHII5
  ENTHIII1
  ENTHIII2
  ENTHIII3
  ENTHIII4
  ENTHIII5
  ENTHIV1
  ENTHIV2
  ENTHIV3
  ENTHIV4
  ENTHIV5
  EX65DT
  EX66DT
  EX67DT
  EX68DT
  EX71DT
  F06N2
  F06O2
  F07
  F07N2
  F07O2
  F07SO2
  F07SO3
  F08
  F08A
  F08AN2
  F08AO2
  F08ASO2
  F08ASO3
  F08N2
  F08O2
  F08SO2
  F08SO3
  F09
  F09N2
  F09O2
  F09SO2
  F09SO3
  F10
  F10N2
  F10O2
```

```
  F10SO2
  F10SO3
  F11
  F11N2
  F11O2
  F11SO2
  F11SO3
  F12
  F12N2
  F12O2
  F12SO2
  F12SO3
  F13
  F13N2
  F13O2
  F13SO2
  F13SO3
  F14
  F14N2
  F14O2
  F14SO2
  F14SO3
  F15
  F15N2
  F15O2
  F15SO2
  F15SO3
  F16
  F16N2
  F16O2
  F16SO2
  F19
  F19N2
  F19O2
  F19SO2
```

```
  F20
  F20N2
  F20O2
  F20SO2
  F21
  F21N2
  F21O2
  F21SO2
  F21SO3
  F22
  F22N2
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  F22O2
  F22SO2
  F22SO3
  F23
  F235
  F235N2
  F235O2
  F235SO2
  F235SO3
  F23N2
  F23O2
  F23SO2
  F23SO3
  F24
  F24N2
  F24O2
  F24SO2
  F24SO3
  F25
  F25N2
  F25O2
  F25SO2
  FDW
  FFIIISO21
  FFIIISO22
  FFIIISO23
  FFIIISO24
  FFIISO21
  FFIISO22
  FFIISO23
  FFIISO24
  FFISO21
  FFISO22
  FFISO23
  FFISO24
  FFIVSO21
  FFIVSO22
  FFIVSO23
  FFIVSO24
  FFPROD
  FIIIO21

  FIIIO22
  FIIIO23
  FIIIO24
  FIIIO25
  FIIISO21
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  FIIISO22
  FIIISO23
  FIIISO24
  FIIISO25
  FIIISO31
  FIIISO32
  FIIISO33
  FIIISO34
  FIIISO35
  FIIO21
  FIIO22
  FIIO23
  FIIO24
  FIIO25
  FIISO21
  FIISO22
  FIISO23
  FIISO24
  FIISO25
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  FIVO22
  FIVO23
  FIVO24
  FIVO25
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  FIVSO22
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  FSW1A
  FSW1B
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 JHII4
 JHII5
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 MFI5
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 MFII2
Economic Optimization Program                                   01/25/01 17:27:26  PAGE     92
                                                         GAMS 2.50A  Windows NT/95/98


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 MFII5
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 MFIII2
 MFIII3
 MFIII4
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 RATEINIII5
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 RATEINTI5
Economic Optimization Program                                   01/25/01 17:27:26  PAGE     93
                                                         GAMS 2.50A  Windows NT/95/98


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Economic Optimization Program                                    01/25/01 17:27:26  PAGE     95
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  TRIIN22
  TRIIN23
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  TSW1B
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  VISCIV2
  VISCIV3
  VISCIV4
  VISCIV5
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  XPROD
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**** REPORT SUMMARY :        0     NONOPT
                             0 INFEASIBLE
                             0 UNBOUNDED
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EXECUTION TIME       =        0.060 SECONDS     0.9 Mb      WIN-18-097


USER: Ralph W. Pike                              G990726:1450AP-WIN
      Louisiana State University, Department of Chemical EngineeriDC267

**** FILE SUMMARY

INPUT     C:\PROGRAM FILES\ADVANCED PROCESS ANALYSIS SYSTEM\GAMS25\DO_ECON
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