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**Control of Gasifier Operations Using Neural
Networks, Task 7.11**

**Topical Report
September 1992 - December 1993**

**Steven Cisney
John Erjavec
C. Narahari Rao**

April 1994

Work Performed Under Cooperative Agreement No.: DE-FC21-86MC10637

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
University of North Dakota
Energy and Environmental Research Center
Department of Chemical Engineering
Grand Forks, North Dakota

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EXECUTIVE SUMMARY

The incentive for this project was to investigate to applicability of a new modeling tool—a system of equations which emulate the human brain, called neural nets—for chemical process modeling and control at the Dakota Gasification Company (DGC) coal gasification plant in Beulah, North Dakota. The specific goals were 1) to determine guidelines for identifying likely candidate processes for the use of neural nets, 2) to screen the various process areas of the Beulah plant, using these guidelines, 3) select a process area to study, and 4) apply neural nets to model that particular process area.

The key guidelines were found to be 1) the process should be a critical component of the whole plant, 2) the process should be important economically, 3) a large amount of data should be available about the process, and 4) the process should not already have a mechanistic model. When these guidelines were used to screen the various plant processing areas, the gasification area was the prominent candidate for the application of neural nets.

Calculations showed that it was possible to save over \$500,000 (the upper limit assuming a perfect model used for control) by increasing the steam-to-oxygen (S:O) ratio. The problem is that when the S:O ratio is increased, more gas liquor is produced, and there is a limit to how much gas liquor can be handled downstream. Thus, if a model were available to predict how much gas liquor would be produced, the S:O ratio could be increased to the operating limits. Even an imperfect model, which would leave some "breathing room," should still be able to capture 50%–60% of the potential savings (about \$300,000/yr).

The performance of the neural net was apparently hindered by the type of data input used. Once the known effects of oxygen flow rate and S:O ratio were taken into account, there was no correlation left between any of the input data and the gas liquor flow rate. This result was verified using regression analysis, so there is likely no problem with the neural net itself. Rather, the conclusion is that the data used did not give any information useful for predicting gas liquor flow. Therefore, in order to apply neural nets to go after the savings, more variables must be logged on a regular basis. The most important variable needed to continue this project is probably the volatiles content of the coal.

The recommendation is to continue this work in the direction indicated. Many other chemical and energy companies have reported using neural nets to great advantage. There is no reason to suspect that this should not be true at Beulah as well.

CONTROL OF GASIFIER OPERATIONS USING NEURAL NETWORKS

1.0 INTRODUCTION

Neural networks have recently been gaining a lot of attention in the chemical and process engineering fields. An artificial neural network, (or "neural net" or simply "net") is a crude model of the human brain. Unlike the rule-based expert systems using deductive logic, the neural networks use inductive logic to "learn" from examples. They can be used to classify, recognize patterns, or capture complex correlations from given data. They are therefore called "natural intelligence systems" and can be thought of as a complement to expert systems in mimicking the functions of the human brain.

Neural networks consist of a set of parallel, interconnected processing elements called "nodes" or "neurons." The connections themselves are called "synapses". The neurons can be thought of as arranged in an input layer, a middle or hidden layer, and an output layer (Figure 1). The hidden layer itself may consist of one or several layers. Data is fed to the input layer, the hidden layer processes the data, and the results are received from the output layer. Because of the inherently parallel nature of neural networks, they are much faster than serial digital computers or algorithms.

Figure 1. Schematic of a neural network.

Although neural networks have been studied for many years and have found application in many fields, they are only recently being applied in chemical engineering. Some of the applications include process modeling and simulation, process control, fault diagnosis, optimization, and modeling of transfer processes.

Neural networks are especially useful to model nonlinear phenomena that occur quite often in process industries. For most of these processes, a mechanistic model may not only be very difficult to solve, but sometimes may be impossible to propose, because of the complexities involved. If there are sufficient data however, (from production logs, etc.) a neural network can be "trained" to recognize patterns in the data, and this network can later be used in the predictive mode to estimate the desired response variables. Thus, even if there is no physical understanding of the process, the neural network can be used as a black box to quantify any complex correlation between the important variables of the process.

Neural networks are also fairly robust to noise (imprecise data). This is an advantage because all real life processes have noise, and traditional methods of obtaining correlations are affected by noise.

Neural networks therefore seem to offer a tailor-made solution to process modeling in that they require little understanding of the process and they are able to utilize available data from production logs even with the associated noise.

The neural net learning algorithms used for chemical engineering applications are relatively few and are readily available as off-the-shelf software. This makes the use of neural nets easy, requiring little or no programming skills.

Given such an excellent tool, it was decided to use it to attempt to solve a practical industrial problem—chemical process modeling for process control purposes. The Dakota Gasification Company (DGC) plant at Beulah in western North Dakota, which produces synthetic natural gas (SNG) by the gasification of coal, was selected as the target site.

The gasification plant at Beulah is large and complex. The total land area of the plant is 535 acres and involves many unit operations and unit processes. The various processes are grouped into separate units, like the shift conversion unit, methanation unit, etc. The most important sector of the plant is the gasification unit, consisting of fourteen Lurgi gasifiers. Not only are the gasifiers important from an operational point, but they also pose considerable difficulties for a priori modeling. It was therefore decided to focus on the gasification unit of the plant for possible application of a neural net.

2.0 SELECTION OF THE PROCESS AND THE INPUT AND OUTPUT VARIABLES FOR THE NEURAL NET

The motivation behind this study was the desire to see if neural networks could be used to model and then control and optimize processes at the DGC plant at Beulah, ND. Since this goal was too broad to achieve as one task, the scope was narrowed to that of modeling a suitable part of the gasification plant using a neural net. The first step was to identify a likely part of the process to model, the second step was to collect the needed data, and the last step was to use a neural net to predict responses from the inputs. In

addition, an economic analysis was done, and the performance of the neural net was compared to that of a polynomial model.

Some of the important characteristics of a process that determine if neural networks can be used for its modeling are as follows (1):

- The process should be a critical component of the whole plant.
- The process should be important economically.
- A large amount of data should be available about the process, as neural nets require lot of data for their training and testing.
- The process should not already have a mechanistic model; or if such a model is available but is computationally extremely complex, the use of a neural network is justified. A good understanding of the principles underlying the process and the critical variables influencing the process are also required.

With this in mind, the Beulah plant was examined for processes that meet the above criteria. Figure 2 shows a simplified flow diagram of the Beulah plant. Since the gasifier area (consisting of up to fourteen gasifiers in operation) is the most critical section of the plant, it was decided to concentrate on it. A careful look at the operation of the gasifiers was then undertaken.

This research revealed the following variables (Table 1) measured at the plant for which data were available for a considerable period of time. The number of data points available for each variable is shown in parentheses. Data are available from March 1, 1990 to March 31, 1992, except for the flow rates, which are available from January 1, 1989 to April 30, 1992. Data for steam-to-oxygen ratio, average gas outlet temperature, and the oxygen flow rate (in terms of the number of equivalent gasifiers) are also available. An equivalent gasifier is defined as having an oxygen flow rate of 245,000 standard cubic feet per hour.

Sufficient data were clearly available for neural net modeling of the gasification process. As mentioned earlier, the gasifier is a critical part of the plant and important economically. Although several mechanistic models were available for the gasification process, they were not totally satisfactory (2). The gasification process therefore seemed to be a suitable part of the plant for neural net modeling, by the criteria of Mathur et al. (1).

From the list of the variables in Table 1, the following were selected as inputs to the neural net.

- Steam-to-oxygen ratio used in the gasifier
- Oxygen flow rate
- Dry, ash-free coal/as-received coal ratio
- Moisture content of the coal
- Ash content of coal
- Sulfur content of coal
- Calorific value of the coal

* Data will be gathered for these parameters.

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Figure 2. Simplified flow diagram of Beulah plant.

TABLE 1

List of Variables for Which Data Are Available

Coal	Raw Gas	Flow Rates
Ratio of Dry, Ash-Free Coal to As-Received Coal (DAF/AR) (757)	Hydrogen (714) Hydrogen Sulfide (714)	Coal (1209) Oxygen (1208)
Calorific Value (757)	Carbon Dioxide (714)	Evaporator Concentrate (1201)
Ash Fusion Temperature (194)	Ethylene (564)	Gas Liquor (1192)
Ash Content	Ethane (714)	Crude Phenol (1208)
Silicon Dioxide Content (252)	Propylene (564)	Naphtha (1206)
Aluminum Oxide Content (254)	Propane (714)	Tar Oil (1213)
Calcium Oxide Content (256)	Butenes (564)	SNG (1211)
Ferrous Oxide Content (256)	Isobutane (564)	
Potassium Oxide Content (255)	n-Butane (564)	
Sodium Oxide Content (757)	Isopentane (564)	
Titanium Oxide Content (252)	n-Pentane (564)	
Proximate Analysis	Oxygen-Argon (714)	
Ash (757)	Nitrogen (714)	
Volatile Matter (210)	Methane (714)	
Fixed Carbon (213)	Carbon Monoxide (714)	
Ultimate Analysis	Heating Values (714)	
Carbon (264)	Btu (714)	
Hydrogen (264)	Specific Gravity (714)	
Nitrogen (248)		
Sulfur (757)		
Oxygen (254)		

The following were selected as the outputs:

- Crude phenol flow rate
- Naphtha flow rate
- Tar oil flow rate
- Gas liquor flow rate

The eleven variables were selected as inputs and outputs for the neural net because the maximum data were available for these, and it is important to have a large data set to train the neural net.

The oxygen flow rate and steam-to-oxygen ratio of the gasifier are the most critical input variables in terms of their effect on the properties of the ash (which in turn affects the operation of the gasifier), the amount of gas liquor formed, and the exit raw gas temperature. Economically, the steam-to-oxygen ratio is an extremely important variable (3). Gas liquor is an important variable with respect to the overall plant performance, because the plant's capacity to treat the gas liquor is limited, and an

overproduction of gas liquor will cause disruption throughout the plant. Although sufficient coal flow rate data were available to be used as an input, coal flow was not used because the oxygen flow rate used determines the amount of coal fed to the gasifier. The coal flow rate is therefore redundant if oxygen flow rate is used as one of the inputs (see Section 7.0).

It should be noted that although large amounts of data were available for these variables, these are not necessarily the most important variables affecting the gasification process. For example, although the coal composition (as given by moisture, ash, and sulfur content) does affect the net outputs (especially the gas liquor flow rate), it is believed that the volatile matter content of the coal is an important determinant of the gas liquor flow rate. However, volatile matter could not be selected as one of the inputs to the net because of the limited amount of data available (210 as opposed to over 700 for other coal properties).

There should be no time delay between the input and output variables. That is, any change in the input variable should cause an almost immediate change in the output variables. If not, the net is being trained on a set of data for which the inputs do not affect the outputs. In a large and complex process plant, this means that the inputs and outputs must be from units that are close together. If the data are not from closely located units, the data should be appropriately time shifted.

3.0 CLEANING THE DATA

Once a suitable part of the plant was identified, and the relevant data were obtained, the neural network was almost ready to be built and trained. First, however, steps were taken to ensure that the data used to train the neural net were of good quality. The data were obtained from daily readings at the plant. A data point consists of the seven inputs (steam-to-oxygen ratio, oxygen flow rate, ratio of dry, ash-free coal to coal as-received, moisture content, ash content, sulfur content, and calorific value of the coal) and the four outputs (crude phenol, naphtha, tar oil, and gas liquor flow rates). The raw data set could not be used to train the neural net because it contained many data points that were widely different from the plant's normal operating range. Although neural nets are robust to noise, they do not function properly when trained on aberrant data.

So it was first necessary to clean the data set in order to use it to train a neural net. That is, the data points that deviated from the daily average by a wide margin were presumed to be due to plant upsets and were thrown out, so that they would not obscure any trends in the data. To clean the data, all the variables were plotted as histograms to help determine which data points were outliers. These outliers were then removed from the raw data, resulting in the cleaned data set.

Another approach that can be used to identify the outliers in a data set is to label all the data points that differ from the mean by more than three or four times the standard deviation as outliers. This approach was not used, because the mean and standard deviation are strongly influenced by outliers. Hence, the mean and standard deviation could not be reliably determined from the data, especially for variables like the properties of coal. However, some variables (e.g., steam-to-oxygen ratio) are very precisely controlled, so that their deviation from the mean is limited to a very small interval. The

scatter plots of the raw and cleaned data of all the variables are given in Figures 3 through 24. Appendix A gives a listing of the data points of the cleaned data set.

As can be seen from these figures, a few of the variables had particularly wide fluctuations. For example, the naphtha flow rate had such a wide range of variation that cleaning it had a dramatic effect, as can be seen from the scatter plots of the raw and cleaned data (Figures 19 and 20). The oxygen flow rate also contains some points that deviate from the average over a wide range (Figures 5 and 6). Oxygen flow rate being an important control variable, such wide scatter in the data is not expected. In contrast, we do not see much variation in steam-to-oxygen ratio. Of the seven input variables, only oxygen flow rate and the steam-to-oxygen ratio are used to directly control the gasifier. (Agent temperature is another control variable used in the plant (3)). The rest of the variables, being the properties of the coal, cannot be influenced and can be considered essentially uncontrollable. It is interesting to note that although the coal properties seem to vary over a wide range, the calorific value of the coal remains essentially unchanged, except for one or two points out of the approximately seven hundred points considered (Figures 15 and 16).

4.0 BUILDING, TRAINING, AND TESTING THE NEURAL NETWORK

The cleaned data was then ready to be used with the neural net. Once a net is built, it is trained and tested to see how well it performs with a given set of data whose output is already known.

A major difficulty encountered in choosing a net architecture for a given problem is the determination of the number of hidden layers and the number of nodes in them. Once this is determined, the net architecture is totally defined. The number of nodes in the input and output layers corresponds to the number of inputs and outputs, respectively, and in general, the more complex the relationship between the inputs and the outputs, the higher the number of hidden nodes required to capture the relationships between them.

Although a neural net can be devised to model any function, however complex, given a set of inputs and outputs, this net is by no means unique, nor the best net for a given problem. Also, no definite rules have been laid down that can be used to design a neural net. This therefore means that a trial-and-error approach is used to obtain the optimum number of hidden layers and nodes.

Once a net architecture is determined, it must be trained. That is, the weights for each of the connections in the net must be determined. The actual procedure of training the net is as follows: To start with, random weights are allotted to each interconnection. The net is fed a set of data for which the outputs are known (training set) and an output obtained. After each presentation, the weights are adjusted to give better agreement between the net output and the actual (known) output. This is done by minimizing the error between actual and predicted values. After a fixed number of passes through the data set, say one or two hundred, the training of the net is stopped (the weights of the hidden and output layer are frozen) and the net is used in the predictive mode to check its performance with a testing data set, generated from the cleaned data set. This last step

Figure 3. Scatter plot of steam-to-oxygen ratio (raw data).

Figure 4. Scatter plot of steam-to-oxygen ratio (cleaned data).

Figure 5. Scatter plot of oxygen flow rate (raw data).

Figure 6. Scatter plot of oxygen flow rate (cleaned data).

Figure 7. Scatter plot of ratio of dry, ash-free coal to coal as-received (raw data).

Figure 8. Scatter plot of ratio of dry, ash-free coal to coal as-received (cleaned data).

Figure 9. Scatter plot of moisture content in coal (raw data).

Figure 10. Scatter plot of moisture content in coal (cleaned data).

Figure 11. Scatter plot of ash content in coal (raw data).

Figure 12. Scatter plot of ash content in coal (cleaned data).

Figure 13. Scatter plot of sulfur content in coal (raw data).

Figure 14. Scatter plot of sulfur content in coal (cleaned data).

Figure 15. Scatter plot of calorific value of coal (raw data).

Figure 16. Scatter plot of calorific value of coal (cleaned data).

Figure 17. Scatter plot of crude phenol flow rate (raw data).

Figure 18. Scatter plot of crude phenol flow rate (cleaned data).

Figure 19. Scatter plot of naphtha flow rate (raw data).

Figure 20. Scatter plot of naphtha flow rate (cleaned data).

Figure 21. Scatter plot of tar oil flow rate (raw data).

Figure 22. Scatter plot of tar oil flow rate (cleaned data).

Figure 23. Scatter plot of gas liquor flow rate (raw data).

Figure 24. Scatter plot of gas liquor flow rate (cleaned data).

constitutes the testing of the net. Every tenth data point was removed from the cleaned data set and used in the testing set, while the remaining data points served as the training set. The testing data set could also have been obtained by randomly removing a few data points from the cleaned file. Usually the testing data set is at least one-tenth the size of the training set. When the net is tested, it is presented with the seven inputs of the testing data set and required to predict the four outputs for each data point. If the net is properly trained, it captures the underlying trends and correlations in the training data set. If not, the net is trained further. The trained net is used in the prediction mode under actual plant conditions. The training and testing procedures are discussed in detail in Appendix B.

In this study, the net was built using NeuralWorks Explorer® from NeuralWare Inc. A net with one hidden layer, twenty-five nodes, an input layer of seven nodes, and an output layer of four nodes was used. This architecture was arrived at by using a hidden layer with twice the number of input and output nodes ($2 \times [7 + 4] = 22 \approx 25$). Increasing the hidden layer to thirty nodes gave no better predictions, so a net with twenty-five hidden nodes was chosen. A net with two hidden layers each consisting of fifteen nodes was also tested and was not found to be any better than the present net. So we did not experiment with other net architectures and settled on a net with twenty-five hidden nodes. Another approximate formula for the number of the hidden nodes, h , in a given net is shown in *Using NWorks* (4):

$$h = \frac{\text{cases}}{10 \times (m + n)} \approx \frac{660}{10 \times 11} = 6$$

where *cases* is the total number of data points available for the training, m is the number of nodes in the input layer, and n is the number of nodes in the output layer. This number seemed too small and was not even tried.

The learning algorithm used to determine the weights from the data was the back propagation algorithm, since this is the one most commonly used to solve chemical engineering problems. The back propagation algorithm is described in Appendix B. The sigmoidal transfer function was used.

Since the back propagation algorithm uses the gradient search method to minimize the error of the net, it is sensitive to the starting point (Appendix B). That is, the starting weights of the hidden and output layers may affect the final results of the net. After building the net, we made sure that the starting point had no effect on the net. This point is fully discussed in Section 5.0. The characteristics of the neural net used are summarized in Table 2.

5.0 RESULTS AND DISCUSSION

As described earlier, training the net consists of repeatedly presenting the net with the training data set until the net is able to recognize the underlying correlations in the data, as shown by its performance with the testing set. Initially, the hidden and output layers have random weights. These weights are then modified such that the error, E ,

where

$$E = \frac{1}{2} \sum_{n=1}^N \sum_{k=1}^K (d_{kn} - o_{kn})^2$$

is minimized over all the K outputs for all N data points in the training set, i.e., $\partial E / \partial w = 0$. The $\frac{1}{2}$ in the definition of E is included to cancel out the factor of 2 resulting when the derivative is expanded. In the above equation, d and o are the desired and actual outputs of the neural net and the subscripts n and k refer to the individual data points in the training set and the specific output in a data point, respectively.

In this study, the performance of the neural net is measured in terms of R^2 values. This quantity is defined as

$$R^2 = 1 - \frac{\sum_{n=1}^N (y_n - \hat{y}_n)^2}{\sum_{n=1}^N (y_n - \bar{y})^2}$$

where, y_n refers to any n th actual output of a data point, and $\hat{y}_n$ refers to the predicted value of the net. The arithmetic mean of the set is $\bar{y}$, and N is the total number of data points. R^2 usually lies between 0 and 1 and gives a measure of the ratio of the variance of the data around the net's predictions to the variance inherent in the data. If the predictions of the net are perfect (numerator = 0), R^2 equals 1; on the other hand, if the net is no better than just the average of the data, then R^2 equals 0. Higher values of R^2 are therefore preferred.

A schematic of R^2 values of the testing and training data should ideally look as depicted in Figure 25. The leveling off of the training curve implies that the net has learned the underlying relationships in the data. It continues to go up slowly as the net "memorizes" the random errors in the data (i.e., it overlearns). As the net starts to learn

TABLE 2

Some Features of the Neural Net

Learning Algorithm	Back Propagation Algorithm
Momentum Term Used	No
Network Architecture	
Input Nodes	7
Hidden Nodes	25
Hidden Layers	1
Output Nodes	4
Transfer Function	Sigmoidal*
Bias Connected	Yes

* The sigmoidal function is defined as $1/(1+\exp(-x + \Theta))$.

all the noise in the data, resulting in an "overfit," the R^2 values for the testing set begin to fall off. This is an undesirable effect, and training should be stopped before this happens. Similar plots for all the four responses were generated to determine when training should be stopped (Figures 26–33).

All the runs were performed on a personal computer with an Intel® 80486 chip having a clock speed of 33 MHz. With the present net architecture, 10,000 trainings take approximately one hour.

As mentioned earlier, the effect of starting point on the net's performance was studied and found negligible (Figures 26 through 33). As can be seen from the figures, not only is the neural net showing exactly similar trends for both starting points, both in its predictions as well as trainings (as given by the testing set R^2 s), but also the maximum R^2 values obtainable are the same with two different starting points. These plots indicate that the appropriate number of training cycles is between 10,000 and 50,000.

The maximum R^2 for the testing set is seen to be 0.6 for gas liquor flow rate, while the minimum R^2 seems to be for tar oil (almost 0). The remaining two variables fall in between in terms of their R^2 values. We can therefore arrange the variables in terms of the net's performance index (from best to worst) as gas liquor flow rate, naphtha flow rate, crude phenol flow rate, and tar oil flow rate.

Figure 25. Training and testing R^2 vs. number of trainings (ideal case).

Figure 26. R^2 vs. number of trainings for the response (crude phenol flow rate).

Figure 27. Effect of starting point: R^2 vs. number of trainings for the response (crude phenol flow rate).

Figure 28. R^2 vs. number of trainings for the response (naphtha flow rate).

Figure 29. Effect of starting point: R^2 vs. number of trainings for the response (naphtha flow rate).

Figure 30. R^2 vs. number of trainings for the response (tar oil flow rate).

Figure 31. Effect of starting point: R^2 vs. number of trainings for the response (tar oil flow rate).

Figure 32. R^2 vs. number of trainings for the response (gas liquor flow rate).

Figure 33. Effect of starting point: R^2 vs. number of trainings for the response (gas liquor flow rate).

Since the net's best prediction gave an R^2 value of only 0.6, we wanted to see if the net had learned all the trends present in the training set. The training R^2 varied from 0.8 (best case) to 0.4 (worst case). Incidentally, the worst response for the training set (0.4, crude phenol flow rate) did not coincide with the worst response for the testing set (0, tar oil flow rate), although the best response for the testing set matched the best response for the training set (0.6 and 0.8 respectively, for gas liquor flow rate). That is, although the net had captured about 62% of the variations in the training set for tar oil flow rate, it seemed to account for less than 0.5 percent of the variations in the testing set. For crude phenol, on the other hand, where the training R^2 was only about 30%, the net was able to capture a bit more (about 3%) of the variations in the testing set.

From the above discussion, it is clear that the neural net currently developed is not very practical for use under plant conditions, with the possible exception of predicting gas liquor flow rates. Some of the possible explanations for this behavior are as follows:

- The intervening units between the gasifier and the output measuring devices were not taken into consideration properly in the analysis.
- Since the data are daily averages, a change in the input may not be directly correlated with the outputs.
- Because the steam-to-oxygen ratio and the oxygen flow rate are used as control variables, the underlying relationship may be obscured by this control action.
- Variables that are important in determining the amount of gas liquor produced (i.e., volatiles composition of the coal) are not included as inputs to the net.

Normally, another possibility is that the data may be bad because of inaccuracies in measurement. Sears et al. (3) have looked at the quality of the data collected at the plant. Based on their study, the possibility of inaccurate data being used for neural nets can be discounted. These points are dealt with in greater detail in Section 7.0.

Since the only net output that was predicting actual performance halfway decently was gas liquor flow rate (R^2 for the testing set of 0.60), it was decided to focus on this variable only. (Fortunately it also happens to be the most critical operationally.) As was mentioned earlier, the steam/oxygen ratio is an important factor in the overall economics of the plant. In a study conducted by Sears et al. (3), it was found that if the steam/oxygen ratio could be increased from the value of 0.385 being used at that time, each increase of one unit (a difference of 0.01) in the steam/oxygen ratio results in a net profit of approximately \$0.5 million per year. That is, the higher the steam/oxygen ratio, the higher the incremental net profit. If the plant were run at the highest possible steam/oxygen ratio of 0.405, on the average it would be making an increased profit of \$1 million per year.

However, an increase in the steam-to-oxygen ratio also results in an increased production of gas liquor. Since the plant's capacity to treat the gas liquor is limited (2900 gal/min, [5]), the increase in steam-to-oxygen ratio should be such that it results in a total gas liquor flow less than or equal to 2900 gpm. From the given gas liquor data, it can be seen that this capacity is seldom reached, resulting in underutilization of gas liquor treatment capacity. In other words, the steam-to-oxygen ratio can be increased

without causing any production disruptions; this increase in the ratio of steam to oxygen can translate into profits, according to Sears et al. (3). The potential net profit that can be realized by running the gasifiers at the maximum steam-to-oxygen ratio was calculated as follows: The change in steam-to-oxygen ratio required ($\Delta S:O$) to increase the present gas liquor flow rate to 2900 gpm is calculated using the Sears' correlation: $\Delta S:O = 0.02 [(2900 - \text{actual gas liquor flow}) \div 19 \times 13]$. The equivalent gasifier has been defined earlier as an oxygen flow rate of 245,000 scf/hr. If the calculated steam-to-oxygen ratio exceeds 0.405, it is reduced to 0.405, since the plant can not have a steam-to-oxygen ratio of more than 0.405. The incremental net profit corresponding to this new steam-to-oxygen ratio is then calculated using the Sears calculations mentioned above ($\Delta \text{Profit} = \$5 \times 10^6 [\Delta S:O / 0.02]$). The results are plotted in Figure 34. A few sample calculations are given in Appendix D. Taking the gas liquor flow rate constraint into account reduces the expected incremental profit to \$0.565 million, which is still a healthy amount.

We decided to investigate what effect coal properties have on gas liquor flow rate, since the effect of the other two input variables, steam-to-oxygen ratio and oxygen flow rate, are well known and are used for control. The coal properties presumably account for most of the variabilities in the gas liquor flow rate.

In order to study this effect, it is first necessary to remove the effects of the steam-to-oxygen ratio and oxygen flow rate on the gas liquor flow rate. The effect of oxygen flow rate on gas liquor flow rate is removed simply by converting gas liquor flow rate to "gas liquor flow rate per equivalent gasifier." The effect of the steam-to-oxygen ratio is removed using the Sears correlation given above.

Figure 34. Incremental net profit vs. steam-to-oxygen ratio.

Once the gas liquor flow rate was corrected for steam-to-oxygen ratio and the oxygen flow rates, the neural net was again trained with the remaining five variables of the coal properties (DAF/AR, moisture, sulfur, ash contents, and calorific value). The resulting performance of the net is given in Figure 35.

This graph indicates that once the effects of the steam-to-oxygen ratio and oxygen flow rate are removed from the gas liquor flow rate, no further trends in the data are dependant on the coal properties. This is the reason for the almost zero value for the R^2 of the training set. This result is somewhat surprising, because it seems to imply that the properties of coal do not have any effect on the amount of gas liquor produced (flow rate). If this is true, and the gas liquor flow rate is a function of steam-to-oxygen ratio and oxygen flow rate only, it can be manipulated by these two variables alone, as is done in actual plant practice. That there is no more information left in the data once the effects of the steam-to-oxygen ratio and oxygen flow rate are removed is also borne out by statistical analysis (see below). It should be noted, however, that not all the relevant properties of coal, e.g. the volatiles content, were included in this analysis.

6.0 COMPARISON OF NEURAL NET AND POLYNOMIAL MODELS

Since the neural net predicted only 60% of the patterns and correlations in the testing data set, it was suspected that the net did not learn all the information present in the training data set. However, since the net's performance curves (Figures 32 and 33)

Figure 35. Effect of coal properties: R^2 vs. number of trainings for the variable gas liquor flow rate.

showed no improvement in learning with an increase in number of learning cycles after 10,000, it was concluded that the net had learned all the information in the gas liquor data. It was then decided to compare the neural net's performance with other traditional empirical modeling tools, specifically with polynomial regression. This comparison also serves to point out whether a better net can be devised to model the data or this is the best performance that can be achieved with the given set of data.

For the comparison to be more effective, we wanted to look at the equation describing the polynomial model and the "neural net equation." Looking at the two model equations gives more insight, such as the relative significance of each of the independent variables etc., than looking at just the predictions of the two models. However, the neural net does not generate an equation for its model, only predictions.

A neural net equation was obtained as follows: since the gas liquor flow rate is strongly dependent on steam-to-oxygen ratio and oxygen flow rate, we considered these two variables only. A two-factor, three-level experimental design matrix was set up.

Figure 36. Gas liquor flow rate as a function of steam-to-oxygen ratio and oxygen flow rate using a regression equation.

Figure 37. Gas liquor flow rate as a function of steam-to-oxygen ratio and oxygen flow rate using a neural net equation.

Steam-to-oxygen ratio and the oxygen flow rate were the two independent variables (factors) and the neural net prediction of the gas liquor flow rate was the independent variable. A regression analysis was then done to give the gas liquor flow rate as a quadratic function of steam-to-oxygen ratio and oxygen flow rates. Figures 36 and 37 show the predicted gas liquor flow rate using the regression equation and the "neural net equation," respectively, as a function of steam-to-oxygen ratio and oxygen flow rate. This model also indicated that only steam-to-oxygen ratio and oxygen flow rates are significant. Indeed, the neural net and regression equations are very similar, as can be seen from their predictions of gas liquor flow rates. In Figure 38, the actual gas liquor flow rate data are plotted as a function of the two significant variables, steam-to-oxygen ratio and oxygen flow rate. It can be seen that the planes in Figures 36 and 37 describe the data of Figure 38 well.

A regression analysis to determine the effect of coal composition was also done using a polynomial model. In this analysis, the training set was used to fit a model, and using this model, the R^2 value of the testing set was determined. This gives a comparison of the neural net performance with the performance of a regression model.

A full quadratic equation in the four inputs was used in the regression procedure. Since interactions of an order of more than two are highly unlikely, only a quadratic model was used. The quadratic model was reduced to only significant terms to obtain the best regression model. This was accomplished three different ways using the statistics package, SAS®, to ensure that the right model was selected: SELECTION = FORWARD, BACKWARD and STEPWISE. The option FORWARD adds terms to the model in the forward direction, starting with only a constant term; STEPWISE is similar to FORWARD, except that variables already in the model stay or leave the model depending on their significance. The option BACKWARD starts with a full model and deletes insignificant terms. The command files to run the three cases and the corresponding outputs are attached in Appendix C.

The final model chosen from these selections is given by the run SELECTION = BACKWARD because that gave the maximum R^2 value for the model. Using this model, the calculated R^2 value of the testing set is -0.03244 , which was comparable to the R^2 value given by the neural net. Since the R^2 value is negative, the polynomial model does no better than the average (in fact, a trifle worse).

Figure 38. Gas liquor flow rate as a function of steam-to-oxygen ratio and oxygen flow rate.

7.0 CONCLUSIONS AND RECOMMENDATIONS

Our calculations show that there is a decent economic incentive for improved gasifier control. The limit on potential savings is \$565,000/yr based on increasing S:O ratio as much as possible (up to its maximum of 0.0405) subject to a constraint on the gas liquor produced. Even allowing for the realities of imperfect modeling and therefore imperfect control, a good model for gas liquor production should allow the capture of a 50%–60% of these savings ($\approx \$300,000/\text{yr}$). It was hoped that neural nets would provide this model. Unfortunately, the modeling efforts thus far have been unsuccessful.

As mentioned earlier, the most likely explanation for the poor performance of the neural net is that it was not trained on data that is most appropriate for the given set of outputs. The availability and amount of data were the main factors in choosing the inputs and outputs for the net, rather than the actual variables in the plant affecting the net outputs. At present, only the variables listed in Section 2.0 are measured and recorded in the plant. For decent performance of the net, more complete data are required. These may even include flow rate measurements that would require new instrumentation.

Another problem is that control actions can obscure effects of variables. For example, Figure 39 shows the neural net predictions as a function of steam-to-oxygen ratio. The line indicates a decrease in gas liquor production rate with an increase in steam-to-oxygen ratio. This trend does not match the experimental results of Sears et al. (3). The apparent contradiction is undoubtedly caused by operator action. The steam-to-oxygen ratio is adjusted to maintain a proper gas liquor flow rate. That is, if the gas

Figure 39. Sensitivity of the neural net to steam-to-oxygen ratio for the response (gas liquor flow rate).

liquor flow rate is too high, the steam-to-oxygen ratio is decreased; if the gas liquor flow rate is less than can easily be handled downstream, the steam-to-oxygen ratio is increased. Therefore, when the data are analyzed, a trend exactly opposite to the actual cause-and-effect trend is observed. So care must be taken to use the actual (known) effect of S:O in a model.

In this study, neural net performance was compared to traditional regression modeling methods to see if any light was thrown on the poor performance of the net. Specifically we were hoping to determine if the problem lay in the type of net used or the data available. Given the very poor R^2 value of the quadratic polynomial model, the net is probably fine. This conclusion is supported by two other factors:

- The polynomial model shows gas liquor flow rate is a function of steam-to-oxygen ratio and oxygen flow rate, independent of coal properties—the same conclusion as the neural net.
- The neural net shows similar trends in the R^2 values of training and testing sets for all the responses, indicating that whatever the net has learned in the training set is almost fully reproduced in the testing set. This means that the low R^2 values of the testing set are not caused by the inability of the net in transferring its learning from the training set to predicting the values of testing set.

8.0 REFERENCES

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APPENDIX A

DATA LISTING

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
1	0.380	3354	0.580	35.66	6.34	1.14	7117	25.61	18.87	97.21	2623
2	0.380	3404	0.579	35.98	6.16	1.08	7067	25.67	19.13	104.80	2578
3	0.377	3425	0.576	36.00	6.35	1.10	7063	26.02	19.48	102.10	2616
4	0.376	3434	0.576	35.77	6.61	1.11	7029	26.29	19.03	114.10	2595
5	0.375	3433	0.572	35.79	7.05	1.09	7052	25.92	18.36	100.90	2590
6	0.376	3454	0.576	36.09	6.28	1.29	7053	25.20	18.61	90.49	2667
7	0.375	3393	0.569	36.10	6.98	1.29	6933	20.18	18.48	70.88	2647
8	0.377	3438	0.576	36.95	5.42	1.10	7055	22.12	18.34	101.30	2570
9	0.376	3403	0.578	36.45	5.77	1.19	7018	27.19	18.30	92.06	1834
10	0.378	3394	0.568	36.50	6.70	1.35	6941	26.83	18.86	102.60	2701
11	0.379	3335	0.571	36.81	6.08	1.25	7040	26.97	18.91	112.40	2749
12	0.378	3410	0.574	36.48	6.16	1.40	7022	26.31	18.59	113.80	2764
13	0.378	3408	0.575	36.60	5.85	1.07	7090	26.49	19.51	97.52	2758
14	0.377	3386	0.567	35.82	7.48	1.25	6983	26.64	19.19	100.10	2751
15	0.377	3382	0.571	36.06	6.84	1.14	6861	26.61	19.15	100.10	2770
16	0.380	3445	0.574	35.72	6.91	1.08	7005	26.76	18.43	107.60	2779
17	0.379	3453	0.570	36.43	6.53	1.33	7060	26.61	18.60	105.80	2771
18	0.380	3459	0.579	36.01	6.08	1.13	7091	26.41	18.65	107.00	2771
19	0.382	3462	0.572	36.27	6.53	1.22	7051	25.76	18.91	100.50	2746
20	0.382	3451	0.579	36.27	5.85	1.02	7051	25.45	18.24	110.90	2765
21	0.383	3449	0.579	35.54	6.56	1.10	7187	25.40	17.78	99.83	2733
22	0.382	3444	0.577	35.68	6.63	1.16	7129	25.45	19.20	100.30	2664
23	0.382	3450	0.578	35.78	6.40	1.15	7105	25.03	18.26	97.40	2646
24	0.380	3432	0.582	35.16	6.60	1.35	7095	26.09	18.07	101.70	2649
25	0.379	3398	0.576	36.32	6.03	1.09	7063	25.16	18.82	107.30	2542
26	0.380	3400	0.576	36.51	5.86	1.17	7122	25.35	19.28	103.40	2639
27	0.380	3358	0.575	36.26	6.21	1.14	7016	25.49	18.82	101.10	2577
28	0.380	3340	0.575	36.72	5.82	1.04	6995	24.94	18.70	80.02	2568
29	0.380	3336	0.575	36.00	6.50	1.09	7028	24.00	19.36	102.20	2589
30	0.381	3303	0.584	36.36	5.29	0.95	7157	26.63	19.09	98.78	2494
31	0.379	3305	0.581	36.71	5.21	0.80	7032	24.32	19.40	103.00	2460
32	0.380	3310	0.583	36.14	5.52	0.97	7190	25.85	18.44	100.50	2649
33	0.380	3311	0.582	36.16	5.69	0.99	7147	26.25	18.60	90.41	2414
34	0.381	3317	0.574	36.19	6.39	1.26	7072	26.30	18.90	114.10	2499
35	0.383	3382	0.583	35.53	6.14	0.95	7136	26.01	18.54	104.70	2562
36	0.378	3389	0.588	35.62	5.59	1.03	7154	25.90	18.02	104.20	2555
37	0.378	3408	0.568	36.53	6.67	1.08	6924	25.84	18.29	104.60	2580
38	0.380	3412	0.579	36.02	6.11	1.06	7079	25.63	17.95	107.20	2579
39	0.381	3396	0.581	35.92	5.99	1.03	7136	25.52	17.86	98.16	2555
40	0.382	3382	0.576	35.31	7.12	1.37	7074	26.40	17.96	97.07	2564
41	0.380	3383	0.577	35.54	6.75	1.10	7063	25.40	17.87	100.60	2563
42	0.380	3383	0.578	34.91	7.28	1.39	7009	25.51	17.81	99.06	2564
43	0.381	3382	0.582	35.37	6.47	1.02	7133	25.75	18.00	105.40	2527
44	0.379	3379	0.587	33.64	7.66	1.25	7140	26.73	17.95	104.40	2584
45	0.379	3382	0.587	34.18	7.14	1.07	7139	27.40	17.67	97.83	2559
46	0.380	3382	0.591	33.58	7.35	1.28	7222	26.63	17.83	110.00	2619
47	0.379	3382	0.590	33.76	7.26	1.10	7078	27.30	17.90	91.51	2647
48	0.380	3382	0.570	35.99	7.00	1.12	6846	26.28	18.61	96.08	2669
49	0.380	3382	0.572	36.02	6.75	1.25	6952	26.55	19.63	93.50	2633

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
50	0.380	3382	0.578	35.50	6.69	1.00	7017	27.84	18.40	103.80	2622
51	0.382	3380	0.585	35.64	5.90	1.06	7113	18.94	12.57	100.90	2636
52	0.381	3329	0.576	35.63	6.79	1.33	7128	28.90	8.70	102.20	2616
53	0.405	2502	0.588	35.35	5.87	0.95	7215	24.85	17.57	76.38	2236
54	0.382	3326	0.580	35.94	6.06	1.14	7111	25.17	20.61	96.47	2780
55	0.385	3240	0.588	35.21	5.95	1.05	7214	24.01	18.44	81.96	2833
56	0.384	3314	0.578	35.16	7.06	1.10	7030	24.16	18.48	100.10	2799
57	0.383	3283	0.574	35.38	7.23	1.10	7048	23.23	18.57	90.11	2800
58	0.383	3301	0.576	35.86	6.52	1.15	7080	23.37	19.05	90.09	2801
59	0.383	3305	0.579	36.02	6.10	1.10	7086	23.60	18.65	96.46	2767
60	0.383	3307	0.574	36.04	6.53	1.04	7023	24.24	18.19	85.67	2754
61	0.383	3281	0.573	35.88	6.82	1.20	7025	24.48	18.41	103.30	2737
62	0.382	3153	0.574	35.98	6.65	1.12	7030	26.27	19.11	94.67	2730
63	0.383	3163	0.574	36.20	6.36	1.17	7015	26.34	19.31	95.52	2728
64	0.382	3365	0.575	35.84	6.63	1.18	7095	23.71	17.07	95.44	2568
65	0.382	3369	0.581	35.63	6.30	1.27	7118	26.64	18.07	110.10	2623
66	0.382	3331	0.587	36.05	5.28	1.04	7094	27.95	16.98	109.90	2795
67	0.384	3300	0.581	36.08	5.82	1.06	7032	35.12	17.57	82.06	2826
68	0.383	3239	0.573	35.26	7.47	1.03	6923	29.55	17.61	97.31	2827
69	0.385	3315	0.574	36.48	6.14	1.33	7031	25.95	18.14	93.40	2737
70	0.384	3220	0.579	36.36	5.73	1.39	7059	25.66	15.65	81.09	2653
71	0.384	3305	0.578	36.14	6.10	1.29	7095	21.68	12.43	96.50	2532
72	0.380	2698	0.584	36.02	5.62	1.12	7115	27.73	13.83	92.30	2692
73	0.390	2177	0.578	36.49	5.69	1.24	7093	25.04	19.41	64.37	2319
74	0.404	2162	0.579	36.58	5.56	1.15	7048	25.08	19.11	76.18	2118
75	0.411	2734	0.576	36.46	5.90	1.21	7010	27.03	17.86	97.10	2117
76	0.409	3214	0.571	36.49	6.46	1.38	6914	25.36	17.79	86.95	2257
77	0.386	3328	0.572	36.91	5.94	1.31	6970	25.02	18.52	100.70	2254
78	0.386	3176	0.572	36.80	6.01	1.48	7010	25.31	18.55	80.59	2666
79	0.386	3045	0.573	36.71	5.98	1.18	6914	26.84	18.16	98.21	2687
80	0.389	3219	0.580	36.21	5.76	1.24	7015	25.07	18.31	94.56	2781
81	0.386	3280	0.567	36.61	6.70	1.11	6909	23.24	16.99	91.46	2614
82	0.386	3305	0.572	36.33	6.51	1.18	6980	25.85	18.44	92.02	2646
83	0.387	3149	0.573	36.62	6.05	1.29	7008	24.89	18.40	86.34	2503
84	0.386	3211	0.575	36.55	5.99	1.06	7065	30.01	18.15	99.96	2587
85	0.385	3290	0.585	35.91	5.59	1.09	7148	25.88	18.04	85.19	2513
86	0.386	3331	0.583	35.96	5.76	1.07	7148	26.33	17.55	97.31	2578
87	0.385	3310	0.586	34.59	6.82	0.97	7127	26.24	17.10	90.03	2706
88	0.384	3311	0.579	36.64	5.43	1.10	7033	31.19	16.63	105.10	2709
89	0.383	3337	0.577	36.01	6.24	1.10	7015	27.14	17.57	95.16	2568
90	0.385	3197	0.573	36.41	6.28	1.19	6964	25.51	17.56	84.05	2666
91	0.383	3247	0.583	35.66	6.06	1.02	7094	26.94	17.05	102.50	2530
92	0.383	3293	0.583	35.90	5.83	0.89	7113	27.85	17.12	82.21	2536
93	0.384	3382	0.577	36.19	6.09	1.05	7027	30.70	17.24	107.40	2674
94	0.385	3312	0.577	36.12	6.15	0.90	7002	28.64	17.88	90.98	2674
95	0.385	3359	0.578	36.25	5.92	1.02	7038	26.65	17.75	94.74	2560
96	0.380	3309	0.573	36.18	6.54	0.97	6958	30.41	17.17	105.70	2623
97	0.381	3303	0.580	36.17	5.83	0.95	7020	26.62	17.85	106.60	2545
98	0.379	3153	0.571	36.58	6.27	0.89	6949	25.16	18.07	78.41	2786

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
99	0.385	3211	0.570	36.32	6.64	1.15	6973	26.86	17.44	64.94	2771
100	0.386	3271	0.574	36.79	5.77	1.05	6939	28.01	17.11	93.21	2770
101	0.387	3323	0.579	36.54	5.56	0.96	7053	21.95	17.96	78.83	2801
102	0.386	3347	0.579	36.06	6.09	1.14	7093	26.98	17.52	102.00	2691
103	0.386	3344	0.577	36.34	5.93	1.01	7084	25.34	16.73	109.00	2510
104	0.385	3339	0.583	35.99	5.68	1.06	7072	25.42	18.15	78.32	2198
105	0.386	3353	0.581	35.81	6.14	1.17	7115	33.85	18.40	97.93	2770
106	0.374	3197	0.578	36.23	5.97	1.10	7043	36.32	17.90	100.10	2707
107	0.387	3329	0.577	36.14	6.18	1.21	7057	27.37	17.29	94.10	2704
108	0.387	3318	0.578	35.99	6.22	1.20	7053	21.34	13.57	105.60	2702
109	0.385	3345	0.583	35.37	6.29	1.20	7089	28.58	17.37	99.40	2680
110	0.402	2406	0.581	35.82	6.08	1.00	7113	27.26	16.83	61.27	1839
111	0.397	2864	0.587	35.00	6.32	0.94	7120	23.97	16.93	94.52	2433
112	0.390	2808	0.588	35.14	6.04	1.12	7182	24.55	16.85	96.85	2338
113	0.388	2873	0.584	35.52	6.08	1.13	7130	30.89	16.85	84.58	2178
114	0.402	2866	0.584	35.64	5.96	1.04	7088	32.22	16.42	83.95	2496
115	0.402	2867	0.592	34.47	6.28	1.04	7217	25.61	16.67	81.51	2447
116	0.389	2962	0.581	35.64	6.30	1.30	7105	26.37	17.02	79.24	2390
117	0.400	2966	0.589	35.24	5.88	1.01	7144	30.56	17.14	95.58	2445
118	0.402	2880	0.581	35.63	6.26	1.01	7094	32.59	17.12	55.16	2464
119	0.405	2873	0.580	35.37	6.68	1.11	7086	39.25	17.49	86.88	2414
120	0.403	2909	0.583	34.96	6.71	1.03	7110	34.35	17.02	72.63	2464
121	0.401	2879	0.582	35.35	6.46	0.94	7034	31.68	16.69	80.39	2475
122	0.402	2950	0.575	36.57	5.90	0.92	6975	33.86	17.05	71.33	2218
123	0.390	2885	0.583	35.57	6.14	1.10	7071	27.84	15.68	66.35	2145
124	0.389	2920	0.583	35.66	6.03	0.89	7157	27.14	15.65	80.42	2329
125	0.389	2933	0.587	35.12	6.16	1.16	7237	30.11	14.78	71.74	2307
126	0.390	2925	0.591	35.41	5.47	1.05	7198	37.98	17.00	90.41	2335
127	0.389	2971	0.583	35.80	5.89	1.09	7111	36.10	16.93	80.71	2413
128	0.388	2736	0.589	35.09	6.06	0.90	7118	39.57	17.17	93.47	2282
129	0.387	2950	0.575	35.64	6.84	1.19	7024	36.78	18.29	88.50	2395
130	0.384	2956	0.588	35.62	5.62	1.03	7080	38.97	17.79	67.91	2417
131	0.387	2980	0.580	36.22	5.73	1.11	7073	29.02	17.84	50.05	2176
132	0.390	3288	0.578	35.88	6.30	1.14	6974	25.79	16.25	74.40	2537
133	0.392	3288	0.574	36.45	6.20	1.10	6922	28.64	16.40	60.41	2663
134	0.393	3304	0.576	36.22	6.18	0.95	6996	37.32	16.44	94.57	2725
135	0.388	2993	0.583	35.68	6.02	1.08	7090	33.30	14.53	89.20	2593
136	0.389	2952	0.580	35.87	6.14	1.47	7064	31.51	13.98	80.43	2517
137	0.389	2969	0.577	36.70	5.58	1.25	7060	27.90	15.38	98.54	2535
138	0.388	2968	0.573	36.57	6.12	1.16	6989	37.18	16.37	79.35	2478
139	0.387	2564	0.575	36.04	6.43	1.19	6990	31.29	17.07	90.98	2283
140	0.387	2491	0.585	35.64	5.90	1.02	7038	28.71	17.49	75.51	2021
141	0.386	2848	0.576	36.00	6.42	1.09	7005	28.73	16.97	102.90	2225
142	0.387	2988	0.588	35.03	6.19	1.20	7129	30.25	17.40	95.72	2233
143	0.387	2988	0.580	35.76	6.24	1.15	7073	32.24	17.66	96.74	2403
144	0.386	2979	0.572	35.59	7.17	1.32	6989	30.19	17.41	99.12	2356
145	0.387	3040	0.584	35.00	6.63	1.33	7153	27.05	17.12	96.86	2358
146	0.386	3066	0.577	36.14	6.20	1.07	7014	25.96	17.30	88.99	2476
147	0.386	3109	0.581	35.13	6.77	1.04	7106	25.19	17.11	82.44	2454

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
148	0.387	3110	0.583	35.67	6.07	1.07	7125	28.35	17.56	81.73	2419
149	0.385	2999	0.580	36.02	5.98	1.08	7166	27.40	16.64	92.28	2353
150	0.383	2930	0.577	35.31	7.00	1.10	7061	26.20	17.01	91.79	2416
151	0.386	3202	0.588	35.32	5.92	1.05	7156	29.18	17.17	91.08	2483
152	0.390	3300	0.577	35.83	6.50	1.23	7062	22.86	16.52	92.66	2599
153	0.388	2891	0.575	36.08	6.41	1.01	7017	24.10	16.55	60.23	2459
154	0.387	2812	0.570	35.98	7.00	1.47	7010	25.02	16.95	66.61	2300
155	0.386	2781	0.578	35.90	6.29	1.28	7155	27.75	16.84	87.96	2416
156	0.388	2818	0.583	35.69	5.98	1.05	7184	36.40	17.07	96.75	2313
157	0.384	2822	0.584	35.92	5.63	0.90	7131	28.41	17.21	86.26	2304
158	0.385	2846	0.572	35.74	7.01	1.38	7062	25.09	16.51	67.25	2408
159	0.385	2910	0.572	36.28	6.51	1.21	7033	27.28	14.83	80.56	2370
160	0.385	2874	0.584	35.96	5.67	1.00	7069	23.97	15.81	89.69	2396
161	0.386	2869	0.575	36.00	6.52	1.19	7085	31.35	5.98	78.44	2327
162	0.384	2806	0.566	36.85	6.52	1.15	6981	12.92	3.95	71.49	2446
163	0.386	2777	0.586	34.85	6.58	1.09	7206	20.59	12.31	84.10	2373
164	0.387	1608	0.585	34.98	6.55	1.22	7185	19.94	11.96	52.02	1378
165	0.391	1591	0.580	35.73	6.30	1.05	7152	23.81	16.99	64.13	1997
166	0.394	1596	0.586	36.15	5.23	0.90	7182	22.72	17.84	51.08	2018
167	0.393	1911	0.578	35.81	6.39	1.03	7115	24.38	17.63	57.86	2036
168	0.387	3139	0.571	36.06	6.81	1.11	7014	25.84	17.71	70.72	2169
169	0.388	2926	0.577	36.04	6.26	1.05	6973	24.32	17.80	60.71	2163
170	0.390	3184	0.575	34.95	7.58	1.14	7080	26.94	17.75	100.17	2607
171	0.391	3345	0.572	35.76	7.00	1.09	7017	27.63	18.19	78.00	2727
172	0.390	3343	0.581	35.68	6.26	1.03	7049	26.74	17.96	92.67	2697
173	0.387	3353	0.579	35.35	6.77	1.10	7079	26.08	17.77	101.57	2698
174	0.387	3344	0.588	34.50	6.74	1.20	7193	26.00	17.63	98.55	2700
175	0.386	3355	0.581	35.26	6.68	1.23	7084	26.38	16.95	103.75	2691
176	0.386	3357	0.568	36.04	7.19	1.25	7036	27.24	17.06	95.07	2691
177	0.387	3357	0.580	35.72	6.31	1.06	7103	32.69	17.82	100.88	2597
178	0.389	3355	0.575	35.87	6.59	1.05	7103	29.08	17.22	86.38	2559
179	0.391	3356	0.577	35.84	6.50	1.05	7078	35.87	17.40	112.51	2626
180	0.391	3364	0.576	35.96	6.45	1.07	7034	22.99	17.79	105.37	2579
181	0.390	3359	0.577	35.57	6.74	1.19	7150	28.17	16.65	115.90	2627
182	0.392	3357	0.578	35.64	6.56	1.10	7165	32.49	17.75	98.20	2448
183	0.394	3353	0.587	34.78	6.50	1.05	7203	29.77	16.14	91.02	2487
184	0.396	3358	0.576	35.66	6.76	1.11	7066	25.48	14.89	109.32	1682
185	0.396	3071	0.580	35.59	6.42	0.94	7064	18.60	9.73	93.49	2196
186	0.397	3365	0.579	35.52	6.55	1.01	7143	16.55	9.16	113.40	2770
187	0.393	3297	0.586	35.13	6.30	1.00	7173	16.00	9.25	101.00	2749
188	0.395	2158	0.571	35.95	6.94	1.22	7015	13.08	8.86	81.46	2226
189	0.391	1611	0.583	34.95	6.74	1.14	7194	19.06	8.92	46.44	1294
190	0.392	1611	0.583	35.84	5.89	0.97	7105	19.94	8.58	62.46	1482
191	0.390	1612	0.586	35.28	6.11	1.10	7177	20.68	9.25	59.37	1376
192	0.389	1611	0.580	35.31	6.71	1.13	7114	19.89	9.14	54.27	1374
193	0.389	1623	0.571	35.27	7.62	1.11	7077	18.46	8.76	48.41	1285
194	0.389	1658	0.569	35.55	7.55	1.09	6893	19.71	9.42	51.13	1272
195	0.389	1618	0.581	35.46	6.42	1.03	7152	19.99	9.22	54.02	1294
196	0.389	1620	0.580	35.63	6.38	1.11	7142	19.44	8.80	47.16	1268

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
197	0.392	1644	0.576	35.23	7.20	1.23	7021	19.50	8.74	53.66	1259
198	0.394	1657	0.581	35.59	6.29	1.16	7147	20.33	9.70	54.47	1340
199	0.395	1655	0.583	35.26	6.47	1.07	7174	20.06	9.49	56.85	1272
200	0.398	2364	0.578	35.16	7.06	1.23	7041	19.31	10.03	59.55	1483
201	0.392	3352	0.583	35.03	6.72	0.96	7104	38.90	16.28	106.60	2566
202	0.384	3376	0.577	35.62	6.70	1.25	7041	38.95	17.08	93.78	2705
203	0.390	3399	0.573	36.47	6.25	1.06	6985	36.90	17.51	109.70	2504
204	0.388	3320	0.584	35.83	5.75	1.23	7068	26.66	16.61	94.36	2692
205	0.386	3315	0.574	36.13	6.49	1.30	6995	27.14	16.83	100.84	2739
206	0.387	3362	0.568	36.14	7.03	1.27	6943	27.06	17.11	97.94	2737
207	0.389	3386	0.577	35.95	6.35	1.01	7059	27.07	17.29	102.00	2703
208	0.388	3390	0.564	36.62	6.93	1.26	6903	26.12	17.05	88.83	2770
209	0.391	3101	0.567	36.09	7.18	1.24	7003	26.07	16.33	85.89	2775
210	0.393	3381	0.564	36.29	7.31	1.17	6911	25.92	17.80	94.47	2779
211	0.390	3376	0.571	35.81	7.12	1.06	6988	26.71	17.25	99.94	2792
212	0.389	3392	0.572	36.01	6.76	1.07	7013	28.72	17.20	98.65	2782
213	0.393	3430	0.568	35.97	7.22	1.16	6934	25.96	17.10	94.86	2617
214	0.389	3353	0.570	35.86	7.18	1.13	6986	26.09	16.83	91.10	2618
215	0.389	3361	0.570	36.01	6.95	1.15	6994	31.75	17.37	120.70	2687
216	0.390	3387	0.581	36.02	5.86	0.94	7114	31.27	17.46	113.20	2694
217	0.391	3382	0.575	35.79	6.68	1.12	7055	31.59	17.08	108.00	2628
218	0.387	3385	0.572	36.20	6.60	1.11	7074	34.52	18.01	102.40	2789
219	0.386	3382	0.568	36.78	6.43	1.13	6986	31.38	17.86	99.61	2727
220	0.387	3367	0.575	36.16	6.36	1.05	6957	32.75	17.47	106.60	2790
221	0.389	3349	0.574	35.44	7.19	1.15	6974	34.57	18.87	109.10	2806
222	0.387	3323	0.572	36.01	6.75	1.10	6972	33.45	18.62	104.60	2801
223	0.389	3376	0.574	35.45	7.16	0.85	7010	32.24	18.27	80.36	2717
224	0.388	3391	0.569	36.49	6.59	1.05	6992	36.48	18.34	92.61	2711
225	0.386	3379	0.579	35.22	6.85	1.32	7096	30.15	18.36	112.80	2600
226	0.385	3286	0.577	35.55	6.73	1.05	7068	31.00	18.13	99.77	2584
227	0.384	3314	0.572	36.53	6.27	0.99	6948	31.65	18.40	105.00	2587
228	0.383	3321	0.567	36.33	6.95	1.08	6928	30.15	18.17	89.18	2597
229	0.384	3310	0.573	36.37	6.38	1.04	7007	30.64	17.21	110.40	2552
230	0.383	3301	0.575	36.50	5.97	1.14	7033	30.16	17.68	98.87	2547
231	0.384	3378	0.571	36.03	6.83	1.01	7037	29.51	17.37	87.92	2598
232	0.386	3085	0.572	36.58	6.23	0.97	6940	34.77	16.50	95.51	2618
233	0.384	3303	0.579	35.61	6.45	1.48	7143	30.66	17.21	100.80	2542
234	0.385	3369	0.581	35.33	6.59	1.03	7072	30.72	17.73	112.90	2513
235	0.386	3374	0.572	35.06	7.77	1.24	7002	32.79	17.65	98.78	2605
236	0.387	3393	0.576	35.33	7.06	1.05	6971	32.00	17.62	106.40	2645
237	0.386	3406	0.577	35.63	6.66	1.24	7042	29.23	17.76	96.54	2486
238	0.387	3367	0.576	35.66	6.73	1.26	6957	29.87	18.19	92.34	2565
239	0.387	3365	0.573	35.50	7.20	1.41	6978	28.96	17.77	99.65	2578
240	0.408	1557	0.577	36.40	5.93	0.91	7059	15.22	9.29	61.43	1387
241	0.401	1673	0.577	35.61	6.67	1.10	7114	15.63	10.24	52.49	1481
242	0.398	1658	0.581	35.54	6.39	1.18	7140	18.04	10.28	44.62	1525
243	0.397	2328	0.587	35.12	6.19	1.04	7099	18.62	9.99	73.79	1726
244	0.389	3225	0.583	35.25	6.41	1.06	7119	27.80	18.05	104.50	2610
245	0.391	2485	0.569	36.23	6.92	1.11	6945	16.65	15.90	73.51	1667

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
246	0.390	2825	0.588	35.29	5.92	1.00	7145	22.50	15.87	88.85	2470
247	0.389	3127	0.583	35.11	6.62	1.05	7083	24.01	17.64	94.22	2578
248	0.387	3296	0.581	35.18	6.75	1.04	7055	23.76	18.54	94.01	2578
249	0.383	3303	0.578	36.51	5.71	0.94	7054	25.85	17.40	90.08	2640
250	0.382	3288	0.577	36.56	5.73	0.97	7023	26.92	17.34	89.43	2599
251	0.384	3192	0.586	35.72	5.68	1.04	7157	25.12	19.09	100.60	2586
252	0.386	3221	0.579	36.14	5.91	1.04	7040	27.22	18.11	75.75	2560
253	0.386	3283	0.575	36.12	6.42	1.17	7055	30.26	16.93	110.80	2578
254	0.383	3312	0.577	35.74	6.53	1.21	7087	30.35	16.93	95.71	2569
255	0.382	3364	0.583	35.86	5.89	1.08	7124	35.44	16.99	117.20	2579
256	0.383	3368	0.577	35.88	6.40	1.15	7076	28.62	17.14	96.70	2646
257	0.384	3366	0.593	34.81	5.90	1.08	7281	27.99	17.46	94.08	2686
258	0.382	3368	0.586	35.11	6.30	1.10	7107	26.42	17.21	92.74	2652
259	0.381	3321	0.576	35.65	6.78	1.22	7024	31.57	16.80	102.80	2568
260	0.382	3305	0.575	35.70	6.76	1.03	7030	29.95	17.95	101.20	2567
261	0.384	3351	0.576	36.20	6.16	1.04	6985	28.90	18.06	107.50	2573
262	0.383	2708	0.575	36.10	6.38	1.11	6908	26.04	14.10	89.99	2403
263	0.384	3365	0.569	35.89	7.18	1.04	6877	26.00	16.48	111.80	2601
264	0.383	3364	0.574	35.88	6.72	1.08	7040	30.15	17.66	106.40	2664
265	0.382	3371	0.572	36.28	6.51	1.19	6988	27.63	17.48	100.30	2681
266	0.383	3363	0.578	35.69	6.47	1.04	7032	27.39	16.50	101.30	2712
267	0.384	3387	0.583	36.00	5.74	1.06	7045	30.62	17.19	108.40	2728
268	0.382	3395	0.566	35.64	7.79	0.96	6868	35.74	17.93	91.46	2724
269	0.383	3392	0.577	35.73	6.53	1.11	7092	32.41	17.50	110.40	2805
270	0.382	3374	0.578	36.51	5.67	1.02	7073	29.55	17.05	106.40	2718
271	0.380	3391	0.578	36.55	5.61	0.93	7062	28.53	17.27	99.20	1683
272	0.381	3409	0.577	36.47	5.81	1.02	7051	29.78	17.10	94.54	2663
273	0.382	3418	0.584	36.22	5.38	0.91	7093	29.60	17.04	106.61	2706
274	0.383	3133	0.582	36.02	5.79	1.06	7150	29.15	16.52	98.60	2550
275	0.381	3324	0.576	36.22	6.19	0.97	7038	27.10	17.35	93.23	2645
276	0.383	3382	0.582	36.21	5.63	0.96	7064	27.62	18.04	96.25	2712
277	0.382	3412	0.573	36.12	6.60	1.22	7049	28.08	18.16	103.57	2750
278	0.383	3411	0.571	36.02	6.91	1.26	7022	29.97	17.59	100.82	2714
279	0.384	3381	0.574	36.06	6.58	1.44	7035	32.42	17.56	99.59	2705
280	0.381	3404	0.575	35.78	6.73	1.21	7016	32.94	17.91	90.09	2715
281	0.381	3404	0.576	36.05	6.34	1.12	7022	32.27	17.67	97.80	2662
282	0.385	3405	0.576	35.61	6.78	1.18	7005	31.88	17.38	86.12	2715
283	0.385	3406	0.584	35.39	6.22	1.30	7161	36.98	17.57	109.63	2677
284	0.384	3421	0.580	36.44	5.57	0.95	7059	35.78	18.83	98.95	2690
285	0.384	3393	0.577	35.82	6.43	1.13	7069	32.78	18.72	110.71	2622
286	0.384	3402	0.572	35.93	6.84	1.09	7039	33.19	18.32	99.80	2698
287	0.385	3409	0.576	35.60	6.80	1.09	7098	33.12	17.10	94.84	2665
288	0.385	3398	0.580	35.62	6.42	1.09	7126	33.05	17.18	106.63	2644
289	0.383	3376	0.579	35.93	6.15	1.10	7044	31.64	17.87	88.86	2638
290	0.385	3368	0.573	35.69	7.05	1.17	6852	32.92	17.78	97.86	2669
291	0.388	3379	0.577	35.59	6.74	1.21	7096	31.22	17.82	101.94	2676
292	0.390	3404	0.581	36.45	5.48	1.04	7069	30.30	18.13	98.14	2735
293	0.388	3412	0.572	35.73	7.08	1.17	7036	32.08	17.73	97.64	2773
294	0.386	3398	0.579	36.29	5.83	1.08	7108	33.87	17.79	91.43	2743

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
295	0.386	3408	0.575	35.82	6.68	1.19	7046	33.82	17.55	98.09	2741
296	0.386	3377	0.577	36.40	5.89	1.08	7113	32.81	17.73	99.55	2728
297	0.385	3390	0.575	36.09	6.39	1.13	7062	33.60	18.11	106.31	2723
298	0.386	3388	0.578	36.12	6.10	0.98	7044	35.29	17.97	97.61	2719
299	0.384	3403	0.572	36.18	6.66	1.04	7039	38.22	17.78	103.47	2760
300	0.381	3398	0.571	36.04	6.87	1.18	7042	33.16	17.47	94.99	2773
301	0.385	3262	0.585	35.30	6.19	1.09	7217	24.90	17.80	94.23	2705
302	0.384	3400	0.581	35.69	6.19	1.07	7129	23.49	17.43	107.42	2066
303	0.383	3414	0.585	35.51	5.99	0.93	7116	34.86	17.72	103.22	2569
304	0.382	3414	0.587	35.72	5.61	0.98	7129	29.56	17.81	96.58	2602
305	0.381	3415	0.584	34.76	6.88	1.17	7193	31.10	17.94	105.98	2572
306	0.379	3416	0.586	34.86	6.57	1.06	7195	31.53	18.57	98.22	2632
307	0.381	3414	0.574	36.22	6.37	1.19	7075	35.07	18.23	91.92	2297
308	0.384	3417	0.568	35.51	7.74	1.32	6905	32.44	18.57	100.67	2614
309	0.386	3399	0.578	35.52	6.69	1.10	7082	28.09	18.49	97.36	3018
310	0.385	3407	0.581	35.93	5.97	0.98	7087	28.64	18.48	78.92	2685
311	0.385	3417	0.570	36.46	6.54	1.10	7015	27.75	18.43	86.49	2759
312	0.386	3405	0.580	36.00	6.04	1.02	7106	29.86	18.35	88.26	2688
313	0.387	3405	0.583	35.01	6.68	1.01	7116	30.87	18.46	88.35	2918
314	0.386	3421	0.579	34.92	7.19	1.25	7126	29.01	18.06	102.15	2962
315	0.385	3417	0.583	35.06	6.63	1.11	7086	28.71	18.38	113.83	2725
316	0.386	3388	0.574	36.79	5.81	1.02	6968	29.91	18.77	90.00	3048
317	0.382	3306	0.569	36.05	7.02	1.33	6932	25.32	18.92	91.88	2114
318	0.384	3210	0.574	36.06	6.55	1.01	6989	28.74	18.14	97.50	2723
319	0.385	3188	0.572	36.35	6.47	0.94	7035	28.22	17.94	87.59	2659
320	0.386	3170	0.573	36.15	6.52	1.06	7030	17.07	17.57	89.29	2611
321	0.386	3223	0.576	36.46	5.97	1.07	7073	16.46	17.75	76.51	2453
322	0.387	3233	0.571	36.05	6.86	1.04	6962	15.81	18.60	83.73	2211
323	0.385	2482	0.583	35.88	5.80	1.09	7198	23.00	16.39	73.34	1803
324	0.384	3117	0.564	36.11	7.52	1.10	6906	22.07	16.06	84.80	2515
325	0.382	3347	0.573	36.56	6.09	0.97	7003	28.05	18.61	101.17	2515
326	0.382	3372	0.580	35.95	6.04	0.94	7091	26.71	18.93	90.48	2589
327	0.383	3410	0.576	36.04	6.32	1.03	7022	25.65	18.59	90.80	2606
328	0.384	3416	0.572	36.02	6.80	1.14	6945	27.28	18.81	96.48	2628
329	0.385	3436	0.573	36.31	6.38	1.12	7009	26.94	18.26	95.62	3006
330	0.381	3422	0.576	36.08	6.29	1.25	7022	27.78	18.28	97.10	3012
331	0.377	3407	0.582	36.20	5.61	1.09	7038	27.09	18.39	100.41	2835
332	0.376	3079	0.579	35.95	6.13	1.26	7043	27.15	16.95	84.72	2525
333	0.378	3001	0.583	35.80	5.89	1.43	7119	26.08	17.13	93.21	2303
334	0.380	3278	0.577	36.40	5.92	1.27	7099	26.49	18.50	92.60	2628
335	0.381	3372	0.579	36.38	5.74	1.16	7038	27.76	16.93	101.73	2754
336	0.381	3373	0.594	34.72	5.88	1.06	7238	26.93	16.78	100.69	2664
337	0.378	3319	0.589	35.84	5.28	1.00	7127	28.61	17.38	97.25	2527
338	0.377	3119	0.579	35.91	6.18	1.24	7070	23.06	17.01	96.12	2616
339	0.379	3325	0.576	35.95	6.45	1.33	7012	27.55	17.74	85.68	2667
340	0.381	3410	0.579	35.66	6.47	1.25	7018	25.86	18.38	93.46	2714
341	0.382	3421	0.582	35.46	6.36	1.11	6981	29.07	18.18	87.49	2722
342	0.383	3419	0.569	36.60	6.54	1.20	6966	27.14	18.43	100.57	2700
343	0.380	3313	0.581	35.95	5.91	1.10	6998	27.45	17.25	93.25	2612

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
344	0.379	3337	0.571	36.10	6.83	1.43	6931	26.32	17.28	80.68	2660
345	0.382	3421	0.572	35.78	7.05	0.95	6940	27.86	17.28	92.47	2706
346	0.381	3391	0.575	36.08	6.43	1.23	7036	30.07	17.32	92.69	2656
347	0.382	3398	0.579	35.61	6.49	1.19	7074	27.63	17.49	94.62	2705
348	0.381	3428	0.578	35.23	6.96	1.10	7045	31.78	17.73	102.14	2738
349	0.380	3407	0.582	35.85	5.95	0.99	7118	25.69	17.08	85.12	2730
350	0.382	3393	0.585	34.95	6.60	1.16	7196	30.06	17.02	96.09	2727
351	0.381	2963	0.578	36.08	6.10	1.00	7010	37.41	16.81	75.81	2636
352	0.381	3276	0.579	35.40	6.65	0.81	7112	31.82	17.48	87.04	2052
353	0.382	3377	0.570	35.40	7.64	1.01	6918	30.77	17.12	77.33	2641
354	0.383	3375	0.581	35.49	6.41	1.11	7027	37.52	16.29	85.78	2617
355	0.382	3376	0.573	36.54	6.19	1.16	7015	34.01	16.47	94.18	2675
356	0.382	3400	0.571	36.71	6.18	1.12	6946	35.99	17.32	82.76	2685
357	0.382	3362	0.574	36.27	6.33	1.22	6947	29.29	16.42	79.68	2714
358	0.381	3308	0.572	36.72	6.05	1.01	6879	27.89	16.89	84.03	2477
359	0.381	3347	0.575	36.28	6.17	1.00	7004	30.90	16.52	89.12	2533
360	0.380	3384	0.578	35.77	6.43	0.92	7016	31.06	17.13	95.28	2724
361	0.381	3302	0.584	35.76	5.80	1.13	7058	32.20	16.75	70.44	2701
362	0.381	3381	0.581	35.67	6.25	1.10	7111	32.88	17.78	101.16	2636
363	0.380	3385	0.574	36.48	6.17	1.10	6997	30.19	19.03	91.71	2690
364	0.380	3370	0.576	35.38	6.99	1.10	6975	30.49	18.16	95.91	2521
365	0.379	3373	0.565	35.74	7.79	1.14	6872	33.10	18.23	95.02	2617
366	0.382	3326	0.576	35.51	6.84	1.20	7088	32.74	18.19	93.57	2617
367	0.381	3377	0.580	35.48	6.50	1.07	7109	33.52	19.05	98.64	2597
368	0.381	3404	0.589	34.68	6.42	1.21	7138	33.74	18.76	103.90	2631
369	0.380	2932	0.564	36.91	6.69	1.24	6889	31.11	15.49	85.77	2160
370	0.379	2853	0.579	36.18	5.91	0.95	7000	34.63	16.63	99.28	2234
371	0.379	2770	0.577	36.14	6.17	1.19	7040	29.43	15.42	91.70	2287
372	0.382	2832	0.581	35.53	6.40	1.09	7065	26.75	15.48	97.50	2280
373	0.396	2874	0.573	36.27	6.42	1.25	6922	30.23	16.32	75.88	2347
374	0.396	2860	0.578	36.00	6.24	1.26	7061	37.30	15.86	98.69	2255
375	0.390	2888	0.588	35.07	6.17	1.14	7150	29.85	15.02	83.95	2271
376	0.387	2880	0.572	36.12	6.73	1.31	6956	29.15	15.38	66.03	2432
377	0.389	2775	0.586	35.79	5.61	1.26	7133	31.74	15.27	103.70	2120
378	0.390	2819	0.580	35.49	6.55	1.11	7043	29.59	15.24	91.13	2495
379	0.389	3173	0.573	36.35	6.38	1.14	6956	34.08	16.03	103.46	2600
380	0.381	3158	0.581	35.77	6.17	1.20	7028	32.42	17.39	109.09	2422
381	0.383	3295	0.586	36.02	5.35	1.16	7058	28.10	17.32	90.15	2262
382	0.381	3313	0.583	36.73	5.02	0.93	7043	32.64	17.31	94.28	2538
383	0.380	3325	0.583	35.68	6.03	1.26	7121	30.31	17.16	92.37	2540
384	0.380	3338	0.580	35.58	6.41	1.13	7106	33.03	17.08	90.68	2452
385	0.380	3381	0.572	36.84	5.96	1.47	6937	32.14	17.31	116.79	2530
386	0.382	3346	0.580	35.48	6.54	1.20	7055	32.07	15.91	124.92	2638
387	0.392	2932	0.575	36.00	6.53	1.35	7065	31.00	15.60	111.62	2476
388	0.391	3009	0.574	35.69	6.92	1.20	7048	30.75	16.26	128.32	2227
389	0.390	2981	0.572	36.03	6.81	1.31	6990	32.96	17.49	127.10	2295
390	0.391	2991	0.574	35.89	6.71	1.20	6972	30.18	16.97	104.87	2291
391	0.391	2993	0.580	35.58	6.40	1.20	7088	31.25	16.76	112.55	2324
392	0.390	2950	0.578	36.00	6.17	1.22	7060	30.70	16.25	93.69	2406

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
393	0.379	2918	0.580	35.25	6.75	1.31	7027	27.66	15.61	92.39	2267
394	0.377	3046	0.578	36.08	6.13	1.10	7105	29.59	15.68	82.91	2229
395	0.376	3014	0.573	36.05	6.70	1.24	6993	30.53	16.24	103.21	2276
396	0.379	3053	0.584	35.68	5.92	1.21	7136	30.52	15.90	95.94	2359
397	0.378	3014	0.580	35.93	6.08	1.20	7052	26.21	16.18	71.44	2303
398	0.382	2983	0.579	35.92	6.14	1.16	7093	31.86	16.43	83.48	2361
399	0.385	3031	0.580	35.04	6.93	1.12	7080	30.49	16.54	75.89	2268
400	0.387	3064	0.573	35.40	7.33	0.98	6980	30.95	16.73	77.46	2347
401	0.388	3012	0.573	35.62	7.06	1.02	7002	31.23	17.02	103.03	2337
402	0.390	2979	0.577	35.74	6.53	1.07	6986	30.01	16.91	97.47	2360
403	0.390	2941	0.576	36.20	6.24	1.31	6992	29.90	16.69	113.26	2406
404	0.390	2904	0.581	35.92	6.01	1.22	7129	28.55	16.57	102.53	2355
405	0.385	2947	0.584	35.41	6.22	1.18	7132	27.65	16.02	94.62	2301
406	0.384	3006	0.573	35.84	6.89	1.29	7026	26.21	16.01	94.62	2315
407	0.384	3265	0.576	35.35	7.02	1.30	7097	30.71	17.16	110.71	2427
408	0.385	3331	0.576	35.64	6.79	1.15	7110	31.00	17.12	82.33	2507
409	0.384	3340	0.573	35.57	7.10	1.26	7045	30.82	16.97	95.42	2732
410	0.386	3340	0.578	35.31	6.88	1.40	7173	30.43	16.56	106.36	2643
411	0.386	3272	0.575	35.80	6.68	1.24	7031	26.34	16.65	83.41	2477
412	0.385	3234	0.578	36.34	5.86	1.09	7004	27.26	13.57	95.78	2358
413	0.385	3248	0.581	35.66	6.25	1.13	7107	25.96	15.18	99.20	2301
414	0.385	3283	0.580	35.89	6.11	1.41	7065	26.02	18.14	103.33	2472
415	0.387	3298	0.579	35.53	6.62	1.20	7063	30.16	17.32	103.09	2815
416	0.387	3314	0.566	35.57	7.86	1.45	6956	28.99	17.39	102.18	2959
417	0.387	3294	0.584	35.39	6.16	1.15	7183	30.32	17.39	118.44	2525
418	0.388	3294	0.584	35.33	6.26	1.19	7168	28.47	17.72	111.84	2576
419	0.389	3259	0.579	35.50	6.61	1.24	7128	28.20	17.62	103.63	2478
420	0.387	3268	0.579	35.70	6.37	1.01	7037	28.00	16.09	99.49	2476
421	0.385	3309	0.572	35.73	7.11	1.13	6928	26.73	16.10	96.96	2422
422	0.385	3306	0.564	36.34	7.22	1.21	6914	26.79	16.30	97.53	2438
423	0.385	3280	0.577	35.57	6.69	1.08	7072	28.13	17.71	100.44	2491
424	0.386	3132	0.585	35.02	6.46	0.96	7118	27.18	15.51	93.27	2440
425	0.386	3288	0.581	35.68	6.19	0.99	7136	27.69	17.84	100.11	2450
426	0.388	3292	0.582	35.55	6.27	1.18	7130	27.24	17.25	100.11	2451
427	0.388	3251	0.580	35.77	6.27	1.29	7120	27.76	17.07	96.93	2429
428	0.388	2766	0.583	35.52	6.20	1.30	7149	24.08	15.41	94.32	2187
429	0.389	2994	0.579	35.77	6.32	1.25	7079	21.10	13.90	97.66	1963
430	0.388	3113	0.571	36.72	6.17	1.29	7001	26.49	17.08	93.45	2485
431	0.385	2592	0.588	34.62	6.58	1.22	7201	21.25	14.03	87.75	1895
432	0.387	3124	0.579	35.69	6.38	1.22	6989	23.81	16.34	90.44	2254
433	0.388	3190	0.591	34.62	6.33	1.07	7218	25.97	18.26	100.93	2332
434	0.386	3175	0.590	35.01	6.13	1.21	7222	25.80	17.81	86.89	2335
435	0.384	3280	0.580	35.87	5.65	1.04	7153	27.26	18.08	97.26	2374
436	0.383	3157	0.590	35.21	6.10	1.04	7146	27.21	17.04	92.40	2297
437	0.384	3342	0.580	35.33	6.59	1.03	7107	27.36	18.22	98.53	2383
438	0.384	3355	0.580	35.62	6.41	1.22	7068	27.83	18.60	91.62	2470
439	0.384	3291	0.580	35.48	6.79	1.33	7097	26.73	17.47	107.61	2466
440	0.383	3272	0.580	36.22	6.27	1.12	7039	26.61	16.85	99.54	2331
441	0.385	2034	0.570	35.89	6.81	1.08	7030	19.95	13.38	58.95	1530

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Napththa Flow	Tar Oil Flow	Gas Liquor
442	0.391	1754	0.570	36.60	5.93	1.02	6965	16.26	10.92	69.88	1346
443	0.389	1884	0.570	37.05	5.79	1.04	7023	16.41	10.87	66.05	1391
444	0.383	2216	0.580	36.27	6.23	1.09	6996	17.97	10.78	56.34	1616
445	0.383	2207	0.580	36.44	5.74	1.01	6998	19.39	11.34	73.05	1685
446	0.381	2785	0.580	35.84	6.46	0.95	7029	22.27	13.37	77.48	1977
447	0.380	3377	0.580	35.96	6.48	1.21	7008	31.57	17.78	89.99	2586
448	0.381	3461	0.570	36.67	6.56	1.21	6977	26.77	17.53	108.86	2539
449	0.382	3347	0.580	35.27	6.77	1.17	7074	29.82	17.21	74.01	2549
450	0.383	3419	0.580	36.03	6.12	1.10	7111	29.42	17.63	106.63	2562
451	0.383	3387	0.580	35.74	6.09	1.06	7075	29.42	17.67	98.32	2622
452	0.382	3394	0.580	35.81	6.23	1.24	7099	31.17	17.42	105.29	2624
453	0.382	3411	0.580	36.08	6.16	1.12	7076	30.47	17.12	104.15	2636
454	0.385	2906	0.580	36.37	6.05	1.16	7091	30.41	16.68	89.94	2498
455	0.381	2865	0.570	36.16	6.43	1.15	7065	29.01	16.06	86.37	2180
456	0.379	2761	0.580	36.35	5.73	0.98	7104	29.00	16.34	95.96	2123
457	0.380	3286	0.580	36.13	6.24	1.11	7060	29.26	17.68	98.74	2468
458	0.383	3388	0.580	36.06	6.43	1.04	7018	30.14	17.20	107.53	2962
459	0.380	3377	0.570	36.25	6.91	1.64	7094	30.44	17.10	105.15	2674
460	0.380	3346	0.580	35.71	6.43	1.00	7105	30.36	17.02	101.15	2600
461	0.380	3371	0.590	35.54	5.61	1.00	7165	30.08	17.85	97.15	2714
462	0.380	3412	0.580	36.04	5.51	1.04	7191	29.33	17.74	100.00	2645
463	0.378	3362	0.580	36.32	5.60	0.98	7119	29.71	17.57	107.98	2598
464	0.377	3394	0.580	36.11	5.87	1.18	7069	28.76	18.17	96.66	2598
465	0.376	3376	0.580	35.46	6.62	1.24	7149	29.56	17.67	106.46	2575
466	0.377	3359	0.580	35.44	6.34	1.21	7141	29.34	17.28	99.92	2575
467	0.379	3346	0.590	36.08	5.37	1.05	7114	31.14	17.18	100.07	2602
468	0.378	2821	0.580	36.12	6.32	1.15	7037	28.95	16.11	88.91	2211
469	0.380	3266	0.570	36.82	6.02	1.19	6865	30.82	17.42	112.96	2569
470	0.384	3346	0.570	36.63	6.65	1.27	7071	35.38	17.30	99.45	2634
471	0.384	3358	0.570	36.53	6.59	1.26	7009	31.89	17.34	111.06	2630
472	0.385	3397	0.570	36.75	6.41	1.16	6952	31.31	17.68	85.12	2822
473	0.381	3386	0.580	36.70	5.67	1.05	6975	34.23	16.90	104.85	2564
474	0.381	3351	0.570	35.91	6.70	1.33	7029	34.48	16.75	107.74	2621
475	0.382	3352	0.580	36.31	5.81	1.49	7144	31.10	17.38	104.18	2672
476	0.383	3338	0.570	36.45	6.08	1.11	7058	38.48	18.07	109.31	2681
477	0.383	3331	0.570	36.23	6.53	1.16	7011	36.04	16.88	107.44	2684
478	0.383	3338	0.570	36.43	6.47	1.04	7015	33.45	17.32	107.74	2641
479	0.384	3387	0.570	36.48	6.07	1.12	6994	30.28	17.86	107.20	2689
480	0.382	3345	0.580	36.14	5.99	1.41	7119	29.65	18.28	113.27	2625
481	0.382	3353	0.580	36.26	6.02	1.28	7163	30.64	18.23	103.75	2657
482	0.383	3383	0.580	36.09	5.76	1.11	7069	29.68	17.97	105.47	2658
483	0.383	3380	0.580	35.89	6.32	1.31	7176	29.82	17.73	106.88	2596
484	0.391	3295	0.580	36.03	5.67	1.32	7101	28.32	17.08	95.58	2679
485	0.387	3210	0.580	35.81	6.32	1.17	7142	29.51	16.08	102.15	2564
486	0.386	3163	0.580	36.20	6.24	1.19	7120	27.89	17.04	102.01	2537
487	0.381	2830	0.570	36.27	6.38	1.18	7062	27.38	15.44	92.55	2309
488	0.381	2646	0.580	36.03	6.19	1.05	7051	26.28	14.53	81.24	2157
489	0.382	2374	0.590	35.17	6.15	1.28	7144	24.38	13.73	69.76	1958
490	0.390	2252	0.580	36.07	6.34	1.25	7097	18.09	12.34	62.14	1886

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
491	0.391	1735	0.570	36.82	6.39	1.05	6994	16.20	9.58	59.69	1482
492	0.391	1809	0.580	36.03	6.07	1.02	7104	16.42	10.04	52.34	1564
493	0.390	1781	0.580	35.90	6.52	1.25	7057	15.78	4.71	59.32	1544
494	0.393	1781	0.580	36.35	6.01	1.13	7022	16.31	6.62	60.42	1526
495	0.392	1788	0.580	36.46	5.79	1.10	7114	16.37	8.60	57.60	1568
496	0.394	1734	0.580	36.25	5.26	1.04	7112	18.16	9.56	53.10	1687
497	0.397	1672	0.580	36.42	5.89	1.03	7089	18.45	9.15	69.52	1652
498	0.397	1649	0.580	36.27	6.06	1.27	7031	19.32	12.20	56.02	1579
499	0.392	1707	0.570	35.58	7.21	1.18	6896	21.22	10.20	53.81	1782
500	0.389	1728	0.570	37.15	5.45	0.98	7073	18.45	9.99	52.22	1561
501	0.389	1838	0.570	36.15	6.41	1.07	7038	21.38	9.75	62.14	1746
502	0.387	2373	0.580	35.64	6.65	1.21	7057	21.11	12.11	61.92	2088
503	0.385	2591	0.580	35.76	6.31	1.17	7148	25.82	13.27	74.85	2140
504	0.388	3373	0.580	35.68	6.40	1.03	7115	31.95	18.36	105.86	2773
505	0.388	3414	0.580	36.18	6.03	0.98	7054	31.66	18.24	94.99	2811
506	0.385	3473	0.590	34.76	6.43	1.05	7220	30.83	18.41	110.36	2752
507	0.381	3394	0.580	35.86	6.10	1.20	6973	30.08	18.00	114.31	2739
508	0.380	3400	0.570	36.22	6.40	1.16	7094	27.84	16.85	104.71	2728
509	0.380	3347	0.570	36.15	6.55	1.08	6987	27.75	16.97	89.06	2698
510	0.382	3305	0.580	35.82	5.84	0.94	7180	30.10	17.58	106.50	2669
511	0.386	3317	0.580	36.06	6.16	1.08	7042	29.95	18.04	110.82	2608
512	0.384	3409	0.580	35.54	6.77	1.10	7026	28.20	20.12	102.55	2672
513	0.384	3424	0.570	35.75	6.88	1.31	7013	29.83	20.33	116.83	2700
514	0.383	3436	0.590	35.31	6.19	1.00	7188	29.61	17.72	104.20	2685
515	0.382	3448	0.570	35.71	6.80	1.23	7136	29.23	17.51	112.50	2697
516	0.378	1668	0.580	35.61	6.52	1.10	7189	14.14	6.87	54.05	1543
517	0.387	1648	0.580	35.68	6.56	1.39	7095	18.43	9.04	46.19	1568
518	0.388	1650	0.590	35.51	5.99	0.95	7160	18.57	9.58	46.94	2354
519	0.390	1740	0.580	35.21	6.57	1.00	7108	18.91	12.29	56.07	2026
520	0.382	2284	0.590	34.95	6.42	1.18	7195	19.61	12.03	59.48	1941
521	0.388	3505	0.570	36.08	6.55	1.13	7022	28.37	17.74	103.60	2761
522	0.384	3536	0.580	35.71	6.13	1.23	7093	31.54	19.78	110.69	2794
523	0.385	3528	0.580	35.76	6.52	1.26	7112	32.47	20.61	107.84	2783
524	0.384	3314	0.580	35.67	6.38	1.19	7183	32.04	18.23	111.15	2619
525	0.383	3516	0.580	36.02	6.13	1.16	7098	31.39	21.70	97.16	2782
526	0.383	3524	0.580	35.74	5.87	1.29	7116	31.62	19.39	101.24	2743
527	0.383	3528	0.580	35.78	6.38	1.27	7142	30.30	19.23	97.87	2833
528	0.384	3530	0.580	36.06	5.74	1.29	7113	32.19	18.94	114.27	2786
529	0.384	3509	0.580	36.32	5.81	1.13	7049	32.01	18.27	93.66	2763
530	0.383	3502	0.570	36.80	6.64	1.37	6939	35.72	18.81	95.34	2757
531	0.384	3512	0.580	35.34	6.39	1.24	7114	33.64	17.12	117.82	2743
532	0.384	3504	0.580	35.31	6.94	1.36	7013	32.78	17.08	110.98	2754
533	0.385	3504	0.570	35.74	7.09	1.43	7054	31.78	16.71	104.77	2769
534	0.385	3473	0.580	35.46	6.78	1.41	7150	31.29	17.04	109.59	2731
535	0.384	3444	0.580	35.93	6.53	1.19	7055	31.04	18.77	98.29	2729
536	0.386	3496	0.570	35.98	6.70	1.13	7097	31.95	18.62	119.14	2736
537	0.386	3532	0.580	35.54	6.90	1.02	7060	31.97	18.06	101.09	2770
538	0.385	3532	0.580	35.33	6.81	1.19	7080	32.00	18.85	119.96	2752
539	0.385	2408	0.580	36.13	6.13	1.14	7079	25.19	15.25	101.78	1975

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
540	0.389	2219	0.570	36.70	5.94	0.95	7082	21.86	12.98	74.94	1833
541	0.388	3186	0.580	36.20	6.01	1.13	7107	27.15	16.31	92.89	2494
542	0.386	3527	0.570	36.03	6.58	1.01	7028	29.34	19.20	112.11	2799
543	0.383	3550	0.570	36.07	6.90	1.20	7019	31.03	19.41	118.42	2802
544	0.383	3547	0.580	36.48	6.02	1.01	7064	33.46	17.42	93.58	2814
545	0.382	3554	0.580	36.16	6.22	1.18	7091	33.64	18.83	100.93	2849
546	0.383	3548	0.580	35.95	6.33	0.99	7134	32.20	19.09	113.32	2792
547	0.383	3499	0.580	36.00	6.46	1.16	7060	32.77	18.88	112.43	2753
548	0.383	3541	0.580	35.68	6.35	1.22	7139	32.57	19.01	111.56	2798
549	0.383	3539	0.580	35.55	6.54	1.20	7139	31.30	18.00	105.08	2788
550	0.382	3526	0.580	36.10	6.28	0.95	7115	32.12	18.21	103.70	2785
551	0.382	3500	0.600	33.94	5.99	0.91	7300	33.05	15.10	105.27	2739
552	0.381	3483	0.580	36.29	6.07	1.02	7083	32.51	19.27	99.52	2781
553	0.381	3491	0.570	37.02	5.73	0.94	7071	34.71	19.76	107.74	2811
554	0.381	3514	0.570	36.54	6.07	0.92	7059	35.16	19.08	104.29	2797
555	0.382	3523	0.580	36.26	6.16	1.00	7042	31.77	19.15	110.31	2820
556	0.382	3497	0.570	36.43	6.53	1.13	7066	31.61	17.80	109.64	2865
557	0.382	3500	0.570	36.92	5.89	1.30	7046	32.00	18.12	127.74	2814
558	0.382	3519	0.580	36.13	6.24	1.02	7087	32.25	18.43	109.18	2833
559	0.385	3514	0.580	35.46	6.86	1.03	6971	31.33	18.39	120.83	2854
560	0.386	3512	0.590	35.05	6.31	0.90	7112	33.05	19.62	126.15	2819
561	0.384	3441	0.580	35.93	6.29	0.96	7027	32.54	18.29	109.91	2755
562	0.383	3419	0.580	35.89	6.31	0.99	6980	31.86	18.23	110.91	2702
563	0.384	3355	0.580	35.89	6.39	1.00	7035	30.80	17.00	93.02	2655
564	0.385	2714	0.580	35.98	5.70	1.01	7149	26.96	16.22	94.92	2134
565	0.387	3482	0.580	36.03	6.43	0.99	7037	31.50	19.20	106.22	2752
566	0.385	3175	0.590	35.78	5.70	1.14	7124	29.29	16.36	96.32	2538
567	0.383	3393	0.570	36.05	6.79	1.25	7014	30.75	18.70	103.00	2675
568	0.385	3428	0.570	35.12	7.40	1.02	7091	30.87	19.03	110.17	2722
569	0.382	3460	0.570	35.89	6.78	1.16	7044	31.58	18.74	104.98	2749
570	0.384	3475	0.570	35.33	7.30	1.06	6974	31.20	19.01	104.74	2819
571	0.383	3440	0.580	36.17	6.32	0.95	6997	32.00	18.65	110.44	2764
572	0.383	3470	0.580	35.73	6.40	0.91	7043	32.00	19.55	103.47	2783
573	0.383	3374	0.580	35.95	6.12	0.95	6969	31.76	18.94	114.38	2740
574	0.382	3420	0.580	35.68	6.46	0.98	7100	32.88	18.53	105.03	2731
575	0.383	3435	0.580	36.05	6.37	0.88	7016	31.91	17.83	97.36	2663
576	0.384	3379	0.570	36.57	6.24	1.25	7007	32.11	18.34	104.62	2672
577	0.385	3432	0.570	37.07	6.04	0.97	6983	31.77	19.29	108.33	2675
578	0.383	3481	0.570	36.55	6.35	1.11	6992	32.20	18.03	107.89	2784
579	0.383	3474	0.580	35.71	6.09	1.20	7081	32.66	18.73	118.64	2736
580	0.385	3466	0.580	35.77	6.66	1.29	7041	32.27	18.84	97.57	2742
581	0.385	3412	0.570	36.09	6.78	1.13	7023	30.00	18.34	109.67	2742
582	0.382	3435	0.570	35.83	6.76	1.42	7065	30.57	18.77	94.48	2707
583	0.383	3484	0.590	36.16	5.34	0.94	7130	26.40	17.03	102.88	2741
584	0.382	3473	0.580	36.40	5.82	0.84	7093	30.88	18.58	116.74	2745
585	0.382	3504	0.580	35.94	6.44	1.04	7068	31.82	18.90	105.01	2778
586	0.382	3480	0.580	36.21	6.20	1.01	7086	32.75	19.01	111.43	2865
587	0.382	3480	0.570	36.07	6.70	1.24	7080	30.28	18.28	97.73	2778
588	0.383	3501	0.580	36.01	6.39	1.12	7081	32.04	18.37	113.09	2797

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
589	0.382	3487	0.580	35.61	6.75	0.92	6959	32.77	18.03	99.82	2723
590	0.382	3510	0.570	36.69	5.94	0.88	6947	32.95	17.50	107.22	2777
591	0.383	3519	0.570	36.67	6.38	1.06	6949	31.93	17.75	103.16	2775
592	0.382	3504	0.570	36.04	6.85	1.14	6929	31.80	17.99	115.52	2766
593	0.382	3521	0.570	36.54	6.66	1.08	7013	32.56	18.37	111.11	2807
594	0.380	3501	0.580	35.77	6.28	0.94	7075	32.18	18.81	116.33	2777
595	0.380	3454	0.580	35.78	6.27	0.95	7056	31.61	17.36	101.79	2724
596	0.381	3476	0.580	35.78	5.97	0.76	7120	31.17	18.92	105.42	2767
597	0.381	3447	0.580	35.59	6.08	0.86	7110	31.67	18.82	109.18	2749
598	0.381	3404	0.580	35.58	5.99	1.11	7130	31.52	18.36	97.76	2703
599	0.382	3442	0.570	36.06	6.53	0.95	7075	30.96	17.68	101.35	2806
600	0.378	3379	0.580	36.43	5.74	0.87	7067	31.00	18.55	115.08	2661
601	0.377	3468	0.580	35.80	6.10	1.05	7085	31.00	18.80	106.74	2749
602	0.379	3521	0.570	35.56	7.18	1.13	7005	31.25	19.08	100.82	2782
603	0.382	3494	0.570	37.06	5.66	0.81	6965	31.86	18.18	111.66	2758
604	0.381	3484	0.570	36.06	6.62	1.07	6984	32.15	18.03	108.99	2724
605	0.382	3492	0.580	36.41	5.76	0.89	6971	32.24	17.49	105.05	2731
606	0.384	3503	0.580	35.45	6.52	1.19	7077	31.36	17.47	104.96	2771
607	0.386	3480	0.580	35.48	6.88	1.33	7033	32.57	16.96	107.17	2746
608	0.386	3471	0.570	36.04	6.50	0.95	6968	31.58	18.28	122.06	2789
609	0.385	3470	0.580	36.01	6.47	0.90	7011	32.91	18.65	100.66	2723
610	0.381	3432	0.580	36.40	6.05	0.86	6954	31.90	13.80	103.11	2744
611	0.383	3398	0.580	36.33	5.81	1.00	7085	31.61	15.45	109.16	2711
612	0.385	3365	0.580	35.82	6.31	0.99	7115	31.11	18.35	111.06	2645
613	0.385	3415	0.580	36.52	5.65	1.11	6992	30.68	19.82	104.17	2780
614	0.381	3467	0.581	36.12	5.77	1.13	7113	26.57	19.02	95.77	2757
615	0.381	3357	0.588	35.69	5.52	1.15	7126	25.07	18.11	94.39	2556
616	0.378	3379	0.577	36.31	5.96	1.12	7106	26.28	17.65	108.50	2567
617	0.379	3381	0.579	35.15	6.99	1.06	7072	25.68	17.34	101.10	2518
618	0.381	3329	0.574	35.99	6.64	1.05	7031	24.53	18.76	82.43	2802
619	0.382	3169	0.576	36.64	5.80	1.14	7075	21.33	14.24	99.33	2636
620	0.383	3218	0.581	36.53	5.37	1.09	7050	23.91	12.25	96.28	2809
621	0.382	3329	0.581	36.00	5.89	1.01	7085	33.12	17.08	93.07	2649
622	0.386	3286	0.582	35.98	5.82	1.22	7042	26.93	17.62	91.09	2677
623	0.390	2871	0.584	35.72	5.91	1.02	7114	37.68	16.18	91.94	2262
624	0.386	3031	0.578	35.92	6.33	1.03	7121	31.30	18.62	91.31	2450
625	0.385	2826	0.578	35.99	6.23	1.11	7081	22.96	17.04	83.59	2335
626	0.391	3345	0.577	35.83	6.47	1.12	7053	25.57	18.13	82.80	2711
627	0.391	3357	0.574	36.20	6.39	1.00	7060	37.77	16.72	99.00	2557
628	0.389	3388	0.586	35.09	6.29	1.04	7129	39.75	17.28	99.16	2635
629	0.388	3357	0.579	35.51	6.63	1.02	6948	38.48	16.76	106.50	2690
630	0.391	3424	0.572	36.10	6.74	1.09	6977	28.35	17.36	92.50	2739
631	0.388	3358	0.574	35.78	6.83	1.15	7008	31.86	17.82	100.70	2801
632	0.384	3341	0.571	36.55	6.34	1.04	7000	30.68	18.52	107.20	2540
633	0.389	3160	0.569	36.00	7.08	1.36	6979	28.88	17.03	98.99	2528
634	0.393	2687	0.585	34.65	6.87	1.13	7141	24.88	13.15	93.60	2200
635	0.383	3358	0.585	35.03	6.48	1.08	7161	28.47	17.13	107.00	2670
636	0.384	3371	0.576	35.41	6.99	0.94	6985	33.72	16.49	103.90	2686
637	0.381	3349	0.579	36.02	6.11	1.05	7078	27.96	17.28	94.94	2665

Run No.	S:O	O ₂ Flow	DAF/AR	H ₂ O	Ash	S	Btu	Phenol Flow	Naphtha Flow	Tar Oil Flow	Gas Liquor
638	0.387	3421	0.575	35.58	6.89	1.40	7061	39.69	18.23	110.33	2689
639	0.389	3416	0.576	35.78	6.63	1.17	7087	30.64	17.92	104.55	2770
640	0.386	3417	0.580	35.49	6.49	1.06	7115	25.35	17.92	105.63	2442
641	0.383	3218	0.576	35.91	6.50	1.04	7025	28.15	18.65	95.24	3089
642	0.381	3403	0.573	36.23	6.42	1.16	6999	25.19	18.79	92.41	2616
643	0.377	2886	0.585	36.23	5.28	1.15	7077	27.03	16.77	86.56	2423
644	0.382	3380	0.573	35.74	6.94	1.14	6934	26.03	17.90	94.88	2680
645	0.380	3386	0.579	35.88	6.24	1.07	7059	34.93	17.22	91.06	2657
646	0.377	2609	0.572	36.59	6.24	1.12	6991	31.20	15.59	93.28	2336
647	0.390	2820	0.585	35.60	5.90	1.17	7110	27.48	15.31	94.90	2199
648	0.378	3011	0.585	35.28	6.19	1.12	7114	28.00	15.20	86.65	2348
649	0.388	2938	0.567	36.16	7.12	1.15	6949	25.27	15.99	95.20	2235
650	0.384	3291	0.578	36.07	6.13	1.26	7073	31.69	18.70	102.22	2741
651	0.384	3323	0.570	35.62	7.41	1.35	7007	27.80	16.65	98.25	2439
652	0.385	2765	0.589	34.80	6.34	1.15	7217	26.47	16.11	90.42	2343
653	0.384	3242	0.580	35.47	6.79	1.21	7121	27.33	17.35	103.53	2383
654	0.381	3336	0.580	36.32	5.28	1.07	7136	29.03	17.33	99.39	2560
655	0.381	3406	0.580	35.75	6.61	1.26	7060	29.63	18.88	93.33	2766
656	0.379	3355	0.590	34.69	6.41	1.34	7290	29.85	16.81	84.86	2626
657	0.381	3006	0.580	35.96	6.51	1.13	7004	31.12	14.94	88.60	2446
658	0.382	3364	0.580	35.77	6.32	1.21	7035	30.71	17.48	96.84	2629
659	0.379	3344	0.570	36.00	6.61	1.20	7039	29.77	18.84	106.14	2583
660	0.379	3246	0.580	35.52	6.98	1.17	7147	28.58	16.47	101.60	2523
661	0.387	2966	0.580	35.25	6.61	1.13	7117	25.48	14.46	88.78	2466
662	0.384	3485	0.580	35.74	6.71	1.29	7122	32.32	20.50	97.23	2814
663	0.383	3525	0.580	36.43	5.60	0.97	7055	31.18	19.01	100.53	2778
664	0.383	3297	0.570	36.77	6.15	1.11	7049	30.70	17.17	92.41	2712
665	0.384	3059	0.570	36.22	6.50	1.04	7039	29.33	18.21	99.86	2410
666	0.382	3504	0.570	36.29	6.40	1.02	7041	32.58	18.42	108.91	2764
667	0.381	3469	0.580	36.09	5.96	0.95	7092	30.95	18.11	101.58	2757
668	0.383	3437	0.580	36.51	5.64	0.86	6995	31.00	18.54	104.39	2707

APPENDIX B

BACK PROPAGATION ALGORITHM

BACK PROPAGATION ALGORITHM

All neural networks contain an input, output, and one or more hidden layers. The input layer receives the data and the output layer gives out the results from the net. The hidden layer does most of the computation. Since it is well known that even just one hidden layer gives sufficient flexibility to fit any reasonable mathematical function, that was the only network architecture considered for the project (Figure 1).

Each node in the input layer sends its value to all the elements in the hidden layer. Each node in the hidden layer in turn multiplies each of its inputs by a weight, sums all the weighted inputs, transforms the sum using an activation function, and transmits this value to each of the elements in the output layer. All the elements in the output layer repeat this process, resulting in the output of the neural net.

The weights assigned to the elements in the hidden and output layer are unknown initially, but are determined during the process of training. A set of data (usually large) with known results is used in the training process. Initially, the weights for each of the interconnections are given random values. These are then adjusted by some systematic procedure (algorithm) to make the predictions calculated by the net better. When the result calculated by the output layer of the net matches the known output within specified tolerances, the net is said to be trained.

One of the most common learning algorithms that finds wide use in chemical engineering is back propagation. Several modifications have been proposed for this algorithm. For example, Leonard and Kramer (6) have proposed a modification of the back propagation algorithm that is claimed to be more efficient. Since different versions of the algorithm are available, only the basic steps of the algorithm will be presented here.

Let us consider a neural net with one hidden layer and one input and one output layer (Figure 1). Although the back propagation algorithm can be used when several hidden layers are present, only one hidden layer is considered here since that is the network architecture that was used.

Let the input vector X consist of I elements $[x_1, x_2, \dots, x_I]$ and the output vector D consist of K elements, $[d_1, d_2, \dots, d_K]$. Each node in the hidden layer sums all its inputs from the input layer and transforms the summation using a suitable function.

Let S_j represent the summation of all the inputs from the input layer to the node j in the hidden layer. Then S_j is given by

$$S_j = \sum_{i=1}^I x_i \times w_{ji} \quad j = 1, \dots, J$$

where J is the number of nodes in the hidden layer and w_{ji} is the weight the j th element gives to the output from i th node in the input layer.

The summation, S_j , is then transformed using an activation function. The most commonly used activation function is the sigmoidal function, although several other

functions can also be used. For example, Kavuri and Venkatasubramanian (7) use an ellipsoidal function, which they claim is better suited for fault diagnoses. The important characteristic required of an activation function is that it should be continuous, bound (preferably between -1 and $+1$ or 0 and 1) and should be continuously differentiable. The sigmoidal function is S-shaped, continuous, monotonically increasing, and asymptotically approaches a fixed value ($+1$ and -1) as the input approaches $+\infty$ and $-\infty$. The sigmoidal function used is given by

$$f(x) = \frac{1}{1 + \exp(-x + \theta)}$$

where θ is called the threshold. In our analysis we do not consider θ (i.e., $\theta = 0$). The derivative of sigmoidal function is given by

$$f'(x) = f(x)(1 - f(x))$$

The output from each node in the hidden layer will therefore be

$$H_j = \frac{1}{1 + \exp(-S_j)}$$

Note that this will be the input to each of the nodes in the output layer. Similarly, the output from node k in the output layer will be

$$O_k = \frac{1}{1 + \exp(-\sum_{j=1}^J w_{kj} \times H_j)} \quad k = 1, \dots, K$$

We now have an output from the output layer O and the desired (or exact) output D . From this we can calculate the error of the net. The commonly used measure of error is the sum of the squared errors, which needs to be minimized:

$$E_n = \frac{1}{2} \|D - O\|^2 = \frac{1}{2} \sum_n (D_n - O_n)^2$$

In the back propagation algorithm, the error is fed back into the network to obtain a better value of the weights for the hidden and output layers. That is, the errors flow backward into the net while the information flows forward—hence the name "back propagation algorithm."

This estimate of error is used to modify the weights in the hidden and output layers by using the generalized delta rule:

$$w_{ji}(m) = w_{ji}(m - 1) - \eta \delta_j + \alpha (w_{ji}(m - 1) - w_{ji}(m - 2))$$

where η is called "the learning coefficient" and varies in value from 0 to 1; the last term on the right-hand side of the equation is called the "momentum term" and is used to speed up the learning rate; again α varies from 0 to 1 and m refers to the iteration number. For the output layer, δ is defined as

$$\delta_k = (d_{jk} - o_{jk}) o_{jk} (1 - o_{jk})$$

and for the hidden layer as

$$\delta_{ji} = o'_{ji} \sum_{k=1}^K \delta_{jk} w_{kj}$$

where o'_{ji} is the derivative of a sigmoidal function. The above equation can therefore be written as

$$\delta_{ji} = o_{ji} (1 - o_{ji}) \sum_k \delta_{jk} w_{kj}$$

Note that in above three equations, the subscripts refer to any node, j , in the output or the hidden layer (unlike in the previous equations where the subscripts i and j referred to the input and hidden layers, respectively).

Once the weights of the hidden and output layers are thus modified, the whole process is repeated until the error reaches a preset tolerance level.

APPENDIX C

SAS® PROGRAM LISTING

```

option pagesize=58 probsig=2;
data colcomb;
  infile 'd:\sas\colcom1.dat';
  input x1-x4 y;
  cx1=(x1-0.582)/0.018;
  cx2=(x2-35.365)/1.785;
  cx3=(x3-6.44)/1.42;
  /* cx4=(x4-1.2)/0.44; */
  /* cx4 neglected because x4 is insignificant; therefore x5 becomes x4 */
  cx4=(x4-7073)/227;
  q1=cx1*cx1;
  q2=cx2*cx2;
  q3=cx3*cx3;
  q4=cx4*cx4;
  i12=cx1*cx2;
  i13=cx1*cx3;
  i14=cx1*cx4;
  i23=cx2*cx3;
  i24=cx2*cx4;
  i34=cx3*cx4;
proc reg;
  model y=cx1-cx4 q1 q2 q3 q4 i12 i13 i14 i23 i24 i34 /
  selection=forward include=4 slentry=0.25 slstay=0.10;
run;

```



```

option pagesize=58 probsig=2;
data colcomb;
  infile 'd:\sas\colcom1.dat';
  input x1-x4 y;
  cx1=(x1-0.582)/0.018;
  cx2=(x2-35.365)/1.785;
  cx3=(x3-6.44)/1.42;
  /* cx4=(x4-1.2)/0.44; */
  /* cx4 neglected because x4 insignificant; therefore x5 becomes x4 */
  cx4=(x4-7073)/227;
  q1=cx1*cx1;
  q2=cx2*cx2;
  q3=cx3*cx3;
  q4=cx4*cx4;
  i12=cx1*cx2;
  i13=cx1*cx3;
  i14=cx1*cx4;
  i23=cx2*cx3;
  i24=cx2*cx4;
  i34=cx3*cx4;
proc reg;
  model y=cx1-cx4 q1 q2 q3 q4 i12 i13 i14 i23 i24 i34 /
  selection=backward include=4;
run;

```

```

option pagesize=58 probsig=2;
data colcomb;
  infile 'd:\sas\colcom1.dat';
  input x1-x4 y;
  cx1=(x1-0.582)/0.018;
  cx2=(x2-35.365)/1.785;
  cx3=(x3-6.44)/1.42;
  /* cx4=(x4-1.2)/0.44; */
  /* cx4 neglected because x5 is insignificant; therefore x5 becomes x4 */
  cx4=(x4-7073)/227;
  q1=cx1*cx1;
  q2=cx2*cx2;
  q3=cx3*cx3;
  q4=cx4*cx4;
  i12=cx1*cx2;
  i13=cx1*cx3;
  i14=cx1*cx4;
  i23=cx2*cx3;
  i24=cx2*cx4;
  i34=cx3*cx4;
proc reg;
  model y=cx1-cx4 q1 q2 q3 q4 i12 i13 i14 i23 i24 i34 /
  selection=stepwise include=4 slentry=0.25 slstay=0.10;
run;

```

APPENDIX D

SAMPLE CALCULATION OF INCREMENTAL NET PROFIT

SAMPLE CALCULATION OF INCREMENTAL NET PROFIT

Two sample calculations involved in the economic analysis are given below.

Consider:

A steam-to-oxygen ratio of 0.38

A combined oxygen flow rate of 13 equivalent gasifiers

A combined gas liquor flow rate of 2623 gal/min

Increase in gas liquor flow rate that can be achieved, ($\Delta G:L$)

$$= 2900 - (G:L) = 2900 - 2623 = 277 \text{ gpm};$$

From the Sears correlation, the corresponding increase in steam-to-oxygen ratio, ($\Delta S:O$)

$$= 0.02 (\Delta G:L) \div (19 \times \text{number of equivalent gasifiers})$$

$$= 0.02 \times 277 \div (19 \times 13) = 0.0224$$

The net profit corresponding to this increase in steam-to-oxygen ratio

$$= (\$0.5 \times 10^6 / 0.02 \text{ increase in } S:O) \times (\Delta S:O)$$

$$= \$0.5 \times 10^6 \times (0.0224 / 0.02) = \$0.6 \text{ million}$$

Final steam-to-oxygen ratio = $S:O + (\Delta S:O) = 0.38 + 0.0224 = 0.402$.

Since the above steam-to-oxygen ratio is less than the maximum used in the plant, 0.405, the steam-to-oxygen ratio can be increased to 0.402 without exceeding the maximum gas liquor treatment capacity of the plant and also realize a profit of \$0.6 million per year.

The following shows the calculations involved for the case when calculated steam-to-oxygen ratio exceeds the maximum, 0.405.

Consider:

$S:O = 0.38$

Oxygen flow = 13 equivalent gasifiers

$G:L = 2578 \text{ gpm}$

$$\Delta G:L = 2900 - 2578 = 322$$

$$\Delta S:O = 0.02 \times 322 \div (19 \times 13) = 0.026$$

With this change in steam-to-oxygen ratio, the final steam-to-oxygen ratio is $0.38 + 0.026 = 0.406$, which is greater than 0.405. Therefore, the steam-to-oxygen ratio will be so increased that the final ratio will be 0.405. So,

$$\Delta S:O = (0.405 - 0.38) = 0.025$$

Net profit corresponding to this increase = $0.5 \times 10^6 \times (0.025 / 0.02) = \0.625 million .

**DATE
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8/24/94

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