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A Detailed Steady-State Control Analysis of an Ethanol-Water Distillation Column

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A DETAILED STEADY-STATE CONTROL ANALYSIS OF AN ETHANOL-WATER DISTILLATION COLUMN

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

David L. Canter

August 1987

DEDICATION

To my wife Karen.

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ABSTRACT

This study addresses the steady-state operation and control of an ethanol-water distillation column. The objective is to develop a clearer understanding of how the control and operation of the column effect the energy consumption. The column control will be analyzed by using the singular value decomposition (SVD) and will be studied at a number of operating conditions. SVD is a useful linear, steady-state tool in the control analysis of multivariable chemical processes. The controller pairing and system evaluation can be ascertained, to a certain degree, by calculating the SVD of the steady state gain matrix. A new method of sensor location called the intersivity index is also presented. The possibility of internal tcomposition sensors is investigated. The column economics will addressed by studying the possibility of dual-ended control and by determining the incremental cost of recovered product.

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CHAPTER 1

INTRODUCTION

In the chemical process industry, distillation columns are a very common and energy intensive unit operation. The energy efficiency of such columns depend on the effectiveness of the control systems of the column and on the conditions under which the columns are operated. To better understand the relationship between these factors and the energy required to make an acceptable product, an ethanol-water column was chosen for a detailed analysis. Ethanol-water was chosen because it is a common industrial separation and is typical of a large class of distillation separations.

1.1 The Ethanol-Water System

The system under study is the purification of ethanol after fermentation. After ethanol has been produced there is a considerable amount of water and a small amount of higher order alcohols (fusel oils) present. In order to obtain the "pure" ethanol, two distillation columns are required. The first column separates the higher order alcohols and most of the water. The product cannot be purified in one column because ethanol forms an azeotrope with water at approximately 86 mole percent ethanol. The remaining water must be separated in an azeotropic column. The first column in this two column system

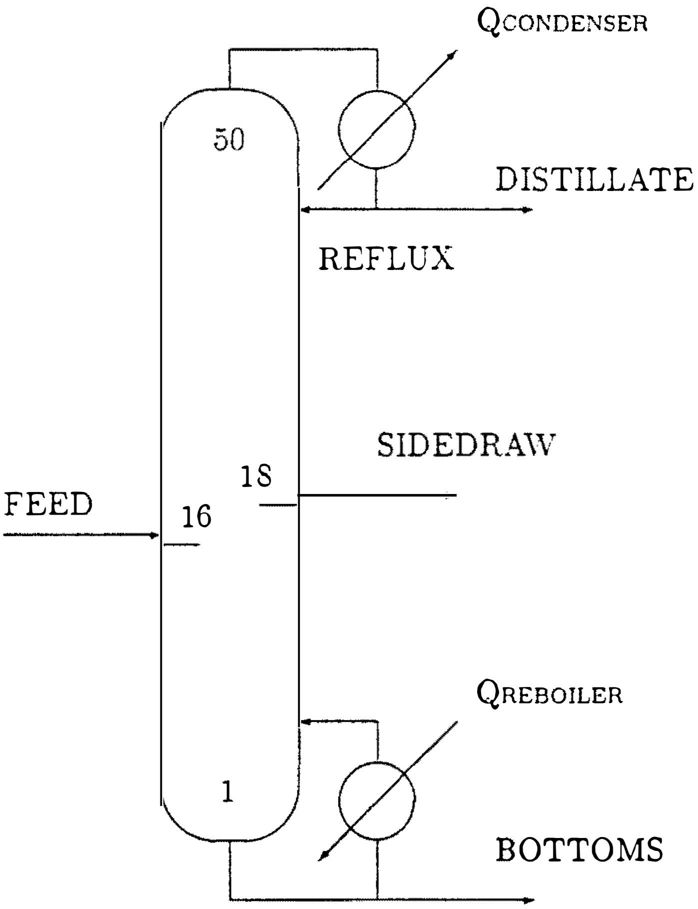

Figure 1.1: Ethanol-Water Column

(typically referred to as the beer still) will the one to be studied. The beer still is shown in Figure 1.1. The entering feed and the sidedraw are both liquids. The reflux ratio for the base case is 7.4. The reboiler duty is 4,129,500 BTU/Hr and the condenser duty is 3,043,800 BTU/Hr. The column specifications are shown in Table 1.1.

Table 1.1: Operating Conditions of the Ethanol-Water Column

Stream ID	Flow lb_{mol}/Hr	Press mm Hg	Temp °F	Composition Ethanol	Water	Fusel Oils
Feed	1072.6	840.0	176.00	0.01700	0.98200	0.00100
Sidedraw	2.5	861.2	201.16	0.05731	0.92766	0.01503
Distillate	21.0	760.0	154.40	0.86049	0.13951	1.93E-09
Bottoms	1049.1	915.0	221.62	2.01E-04	0.99899	9.86E-04

1.2 Operation Considerations

There are several important considerations in the operation of this system. The most obvious objective is to recover as much ethanol as is feasible. Another important factor is the fusel oils (higher order alcohols). The fusel oils are usually extracted from the column by the use of a sidedraw. This is performed in order to keep the fusel oils from "banding up" in the column. If the fusel oils are not purged properly then they will build up in the middle of the column and degrade the effectiveness of the separation. The fusel oil build-up may also affect the relationship between composition and temperature at the control sensor. The sidedraw will be studied in terms of the effect of its location and flow rate on the operation of the column.

Another major consideration in the study is the selection of the best first level control strategy for dual-ended control. This involves selecting the type and location of the sensors as well as selecting which flows will be used to control the column inventory and which flows will be manipulated by the control strategy.

The last major consideration is the effect of the column operation on the economics. In an existing column one of the largest costs is due to steam usage. Some manufacturers use a large excess of steam in order to increase the recovery of ethanol. There is a point of diminishing returns, above which the cost of steam will exceed the value of the ethanol recovered. With today's high cost of energy it is necessary to minimize the energy usage, yet still maintain product specifications.

CHAPTER 2

BACKGROUND

There have been several control techniques applied to distillation column control. The emphasis of research seems to occur in the areas of modern and advanced control. While some of these techniques look promising, there is still a need for research in the basic operation of the column and the first level of column control.

2.1 First Level Distillation Control

First level control strategies deals with the identification and proper pairing of the controlled and manipulated variables. There are five basic variables to be controlled in an ordinary distillation column.

1. Column Pressure
2. Condenser Level
3. Reboiler Level
4. Distillate Specification
5. Bottoms Specification

There are five possible manipulated variables to be considered to control these variables.

1. Condenser Duty
2. Reboiler Duty
3. Reflux Flow Rate
4. Distillate Flow Rate
5. Bottoms Flow Rate

One major aspect of the first level control problem is to determine the proper pairing between the manipulated and controlled variables. Since pressure is usually controlled with the condenser, the first level problem is reduced to the four manipulated variables and four controlled variables that remain. Mathematically there are 24 possible schemes, however only 3 are practical in terms of a typical distillation column. Two of these schemes are designated as material balance schemes, meaning that one of the two manipulated variables directly manipulates the flow of a product stream (distillate or bottoms) while the other manipulates directly (or indirectly) the column's energy input. The third scheme is a more conventional control scheme using the reflux and steam flows to control composition [12]. In all three schemes the manipulated variables that are not used to control composition are used to control the levels in the accumulator and reboiler. There is also the possibility of using the reflux ratio (reflux flow rate/distillate flow rate) as a control valve in the schemes using the reflux rate as a composition control valve [35]. This adds two more schemes to the existing three. The five control schemes that result are listed below.

1. Steam Flow — Reflux Ratio (QR)
2. Bottoms Flow — Reflux Ratio (BR)
3. Distillate Flow — Steam Flow (DQ)
4. Reflux Flow — Steam Flow (LQ)
5. Reflux Flow — Bottoms Flow(LB)

Historically the distillate and bottom compositions were not controlled variables. The distillate flow rate was used to control the condenser level and the bottoms flow rate for the reboiler level. The steam and reflux flow rates were used to "indirectly" control the endpoint compositions. This method works for almost any column but always results in high energy costs since this mode requires the column to be run at high steam rates and high reflux rates to ensure product specifications.

The high energy cost resulting from the method discussed above is the impetus for controlling the endpoint compositions. Composition control is accomplished by manipulating the setpoints of the first level control strategy to hold the product specifications to the desired value. The composition can be measured directly using an analyzer or can, in many cases be measured indirectly using temperature. A common method is to use a cascade control strategy. A sensor measures a variable that gives information on the endpoints and uses that value to set the set point on the flow controller associated with that section of the column [20]. It is also common for the measured variable to be used to directly set the proper control valve.

2.2 Sensor Type

It is very common to use temperature to infer the composition of the product streams. Temperature is related to the composition through the vapor-liquid equilibrium (VLE) relationship for the mixture. One necessary condition for using this inferential method accurately is for the pressure to be held fairly constant or the measured temperature should be mathematically compensated for any pressure variations [51]. The temperature used to infer the composition should be sensitive to changes in the manipulated variables. To accurately infer the composition from the temperatures the mixture should also be binary.

Direct composition control has also been applied to distillation columns [2,31,42,46,48]. Most of these studies deal only with the endpoint compositions as the measured variable. The main problem with using direct composition measurements in the past was the slow response, cost and reliability of the analyzers. However, advances in analyzers have been occurring in the past several years and their use is becoming more feasible.

2.3 Sensor Location

One important aspect of controlling distillation columns is the selection and location of the control sensors. For temperature control schemes a rule of thumb which has commonly been used is to place the sensor six trays from the top and/or bottom. The top and bottom temperatures have also been used as the control sensors. It is also common to see the top and/or bottom compositions used in composition control. The trays selected from these rule of thumb techniques are not usually very sensitive to column changes. In general, these heuristic approaches are not the best sensor locations, though at times some of them work well.

A better way of selecting the sensors is to study the entire array of possible sensors. Hopefully a more sensitive tray will result from such an analysis. One such location method that is sometimes used is to select the tray with the maximum slope on the temperature profile. Tolliver and McCune [58] state that "the optimum control plate location is where the largest symmetrical temperature deviation exists" for parametric studies on the manipulated variable. These last two methods are however only for single-ended control, because there is usually only one such point in a column or two that are adjacent to each other.

A dual-ended location scheme called the principal component method has been applied to distillation columns by Moore [36]. This method is a subset of the singular-value decomposition (SVD) analysis. It results in temperature locations that can be similar to some of the single-ended strategies discussed above, but they can also be very different. The modified principal component method has also been used with some success by Moore et al. [38]

2.3.1 Sensor Location Evaluation

Some preliminary evaluation of the effectiveness of the sensor locations on the control problem must be made. There are several methods of studying the interaction of a multivariable control scheme, the most acceptable one being Bristol's relative gain array (RGA) [5]. The RGA has been extensively applied to distillation control [33,52,62,63]. Most of these applications only address the 2×2 system of top and bottom composition (or temperature) controlled by reflux and boilup. One problem in the use of the RGA is that it is extremely time consuming to consider all of the various combinations of sensor locations. The singular-value decomposition (SVD) analysis, on the other hand, provides a quick and efficient method of culling out the less desirable sensor locations. Once the choices are narrowed down, the RGA can be used in conjunction with the SVD analysis to evaluate the much smaller subset of possible control configurations. The RGA should still be used because it possesses some qualities that the SVD analysis does not have. For example the RGA alerts the user of possible problems that could occur when a loop is decommissioned [51].

CHAPTER 3

ANALYSIS TOOLS

3.1 Distillation Simulation

In order to study the effects of various operating conditions on the control of the ethanol-water distillation column, a rigorous stage-to-stage steady-state computer simulation will be used [13]. The simulation employs the Naphtali-Sandholm convergence method to achieve the desired steady-state [40]. The simulation gives steady-state values for a multicomponent, multi-stage distillation. The program will allow up to 10 components and up to 100 stages excluding the reboiler. There can be up to 10 feed streams and 9 sidedraws. Efficiency and heat profiles may be placed on the column in the simulation. If the reboiler duty is to be set, that is accomplished by imposing a heat profile on stage 1. The program requires the column operating parameters given in Table 3.1 as part of the input.

Unlike some simplified models this simulation retains most of the nonlinearities that are present in a real distillation column. The main simplification is that no hydraulics are used in the calculations. The pressure profile is taken as linear between the top and bottom pressure given in the input.

Table 3.1: Necessary Parameters for Distillation Simulation

Feeds	Sidedraws	Distillate	Bottom	Reflux	Top
Number	Number	Flow Rate	Temp	Ratio	Temp
Location	Location		Pressure	Temp	Pressure
Flow Rate	Flow Rate				
Comp	Phase				
Temp					
Pressure					
Phase					

3.1.1 Physical Properties

In order to execute the steady state distillation simulation, one must have a large amount of physical property and vapor-liquid equilibrium (VLE) data along with column operating conditions. The physical properties include some constants such as molecular weight and molar volumes. Most of the data however is in the form of polynomial equations of second , third or fourth order with temperature being the independent variable. The data that appears in this form includes heat capacities, densities and heats of vaporization. The Antoine constants are also needed for vapor pressure calculations.

The vapor-liquid equilibrium characteristics of the mixture can be input from several different equations. Liquid activity coefficients can be calculated from the Wilson [64], NRTL [44] or Scatchard-Hildebrand [9] equation. The liquid phase can also be assumed ideal ($\gamma = 1$). Wilson constants are readily available in several references [16,21]. The equation is also very good at fitting highly nonideal systems . The NRTL equation is an extension of the Wilson equation for immiscible liquids with a third parameter. The Scatchard-Hildebrand equation (also known as the Chao-Seader correlation) is designed for hydrocarbons and light gases [19]. The Wilson equation will be used in the simulation because of availability of the constants and applicability to the problem.

The fugacity can be calculated from the Redlich-Kwong equation of state [56], Vapor phase association model or can be assumed to be ideal. The association model is designed for carboxylic acids and other highly polar compounds that might associate to form higher molecular weight compounds . The Redlich-Kwong equation is a common basis for estimating fugacities [56] and will surely be more accurate than an ideal assumption. The only inputs needed that are not input elsewhere are the critical temperature and critical pressure of each component. The Redlich-Kwong is the most appropriate for the system being studied.

3.2 Singular-Value Decomposition

An important tool in the analysis and control of multivariable processes is the singular-value decomposition (SVD). Mathematicians defined and developed the computational procedure for SVD several years ago, and it is discussed in several references [7,26,41]. The calculation is very rigorous and is laid out in several algorithms [17,25,28]. There are also a number of mathematical packages that include the calculation of the SVD [66,67,68,69]. The SVD analysis reveals important information on the gain matrix of a multivariable process.

The SVD of a matrix discloses information on the four fundamental subspaces, the rank and the closeness of the matrix to singularity. Any $m \times n$ matrix $\mathbf{A}$ can be decomposed into three matrices of the following form:

$$\mathbf{A} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T \tag{3.1}$$

where

- $\mathbf{A}$ is an $m \times n$ matrix
- $\mathbf{U}$ is an $n \times n$ orthogonal matrix
- $\mathbf{V}$ is an $m \times m$ orthogonal matrix
- $\mathbf{\Sigma}$ is an $n \times m$ matrix

and

$$\mathbf{\Sigma} = \begin{bmatrix} \mathbf{S} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \tag{3.2}$$

Where $\mathbf{S}$ is a diagonal matrix with the diagonal elements being the singular values $(\sigma_1, \sigma_2, \ldots, \sigma_r)$ arranged in decreasing order. The singular values are the eigenvalues of $\mathbf{A}^H\mathbf{A}$ and $\mathbf{A}\mathbf{A}^H$ ($\mathbf{A}^T\mathbf{A}$ and $\mathbf{A}\mathbf{A}^T$ if the matrix is real). The four fundamental subspaces of the matrix correspond to the linear transformation $\mathbf{A} : \mathbf{x} \rightarrow \mathbf{y}$. The SVD of $\mathbf{A}$ can be written as follows:

$$\mathbf{A} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^T = \mathbf{U}_1\mathbf{\Sigma}_1\mathbf{V}_1^T + \mathbf{U}_2\mathbf{\Sigma}_2\mathbf{V}_2^T \qquad (3.3)$$

The matrices $\mathbf{U}$ and $\mathbf{V}$ are partitioned such that all products can be formed. The importance of each partition is explained below.

1. The columns of $\mathbf{U}_1$ form a basis for the image $[\mathbf{A}]$ which is all possible outputs of $\mathbf{y} = \mathbf{A}\mathbf{x}$
2. The columns of $\mathbf{U}_2$ form a basis for the image $[\mathbf{A}]^\perp$ and correspond to all values of $\mathbf{y}$ which are not possible outputs.
3. The columns of $\mathbf{V}_1$ form a basis for kernel $[\mathbf{A}]$ which is the values of x which satisfy $\mathbf{A}\mathbf{x} = \mathbf{0}$.
4. The columns of $\mathbf{V}_2$ form a basis for the kernel $[\mathbf{A}]^\perp$ which is the orthogonal complement of kernel $[\mathbf{A}]$ and corresponds to all values of $\mathbf{x}$ such that $\mathbf{y} = \mathbf{A}\mathbf{x}$ has nonzero output $\mathbf{y}$.

The rank of the matrix is equal to the number of nonzero singular values (r). The closeness to singularity of a matrix is determined by the condition number ($\kappa = \sigma_1/\sigma_r$). The larger the condition number the closer the matrix is to being singular.

3.2.1 Scaling

Much emphasis has been placed on the scaling of SVD in the literature [1,29]. Unlike the RGA, the SVD is sensitive to the scaling of the gain matrix. Several researchers have studied the effects of various scaling techniques. One method given attention is equilibration [14]. Equilibration can reduce the condition number but the scaling order can give widely varying results. Geometric scaling is also a popular method [15]. This method also suffers from the scaling order problem. There are also several "optimal" scaling procedures in the literature that attempt to get all of the elements to be of the same order of magnitude [61]. There is not an ideal scaling method for a general matrix [3]. One problem that is present in every method discussed here is that they may not represent the actual physical system.

A physical scaling method can be used to accurately represent the problem that the control system must deal with. In this method each sensor change is divided by the span of the sensor [35,37]. Each manipulated variable change is divided by the range of the manipulated variable. The scaled gain element is the scaled sensor change divided by the scaled manipulated variable change. For example, unscaled elements for a temperature sensor related to the reboiler duty would be °F/BTU/Hr while the units of the scaled gain element would be % change in temperature/% change in reboiler duty. While the spans and ranges are not known in a simulation, they can be approximated by using the base case values for the sensors and manipulated variables. This is equivalent to the base case values being at about the same percent of the spans and ranges for each variable.

3.2.2 Application to Distillation Column Control

A steady state gain matrix which relates the inputs (manipulated variables) and outputs (stage temperatures or compositions) of the process can be studied by the SVD analysis [13]. After the decomposition is formed, several important aspects of the control can be ascertained.

1. Condition number ($\kappa = \sigma_{max}/\sigma_{min}$) — The condition number gives an indication of the controllability of the system [13]. A small condition number (close to unity) represents an easily controlled system, while a large condition number indicates that the system can only be driven along one vector direction. For all practical purposes, the column has only one degree of freedom. Thus dual-ended control would not be recommended. The cutoff value between large and small condition numbers depends on the system but it is usually taken to be about 100–200.

2. **U** matrix — The columns of the **U** matrix give an indication of the best temperature sensor locations. The highest absolute values in the respective columns correspond to the trays that are most sensitive to column disturbances and therefore are usually the best sensors. If the condition number is small enough that both ends can be controlled then both sensors can be determined from this analysis.

3. $\mathbf{V}^T$ matrix — The $\mathbf{V}^T$ matrix indicates which manipulated variables or combination of manipulated variables has the strongest effect on the system. It may be used in conjunction with the **U** matrix to determine the strongest pairing of manipulated variables with sensor locations. The manipulated variable which corresponds to the largest absolute value in the first row of $\mathbf{V}^T$ has the largest effect on the system and should be paired with the sensor in the first column of the **U** matrix. The manipulated variable associated with the next highest absolute value should be paired with the sensor in the second column. If there is a control scheme that has a third manipulated variable, such as a sidedraw, then the third highest magnitude column should be paired with the sensor in the third column of the **U** matrix.

CHAPTER 4

OPERATIONAL STUDIES

4.1 Base Case Operation

The column is operated at the conditions discussed in Chapter 1. Some other important aspects of column operation can be shown graphically in the profile plots. Profile plots are plots of a variable that changes with each tray versus the tray number. The two main types to be discussed here are temperature and composition profiles.

Inspecting the temperature profile in Figure 4.1 shows that most of the temperature change occurs between trays 15 and 21 as the temperature falls from approximately 100 °C to 82 °C. The overall temperature change is only from 105 °C to 78 °C. Approximately two-thirds of the temperature change occurs in only seven of the fifty trays. The ethanol composition profile in Figure 4.2 further illustrates the fact that a small number of trays do most of the work. The trays in the range 17 to 30 change the ethanol composition for 0.04 to 0.74 mole fraction. Which means that about 80% of the separation is accomplished in less than one-third of the total number of trays. The water composition profile in Figure 4.3 illustrates the same point. Figure 4.4 shows that the fusel oils peak at about tray 18 or 19. This illustrates the need for a

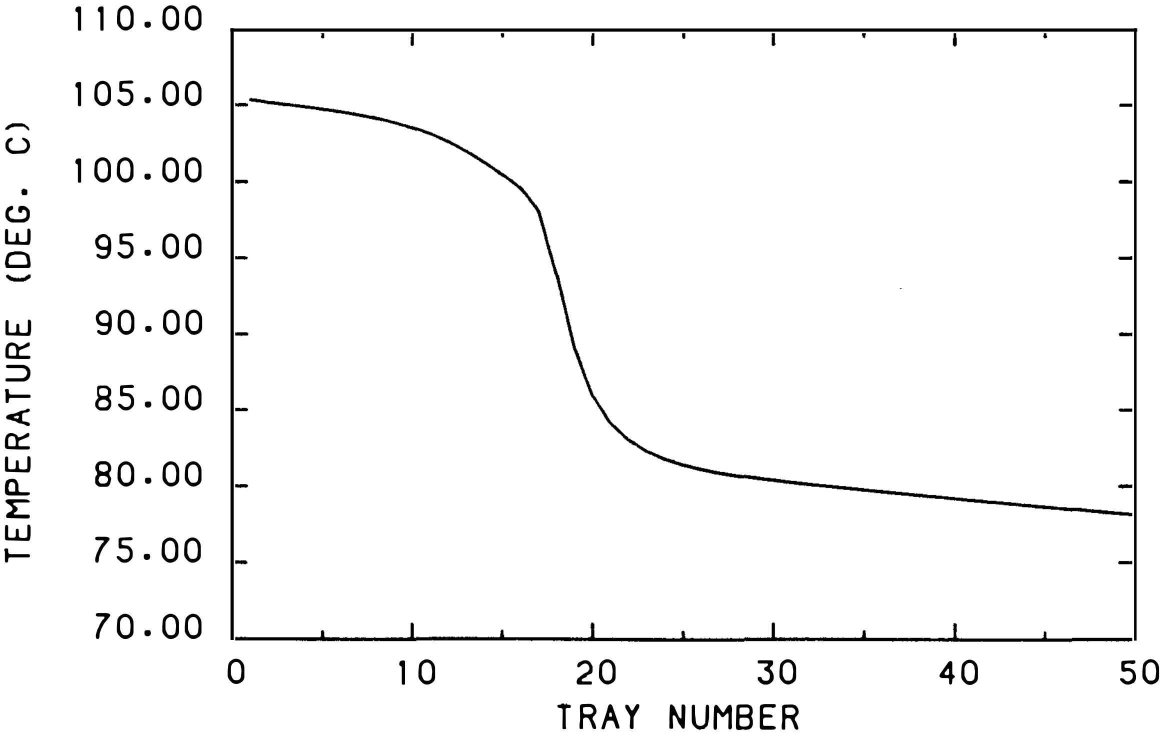

Figure 4.1: Temperature Profile

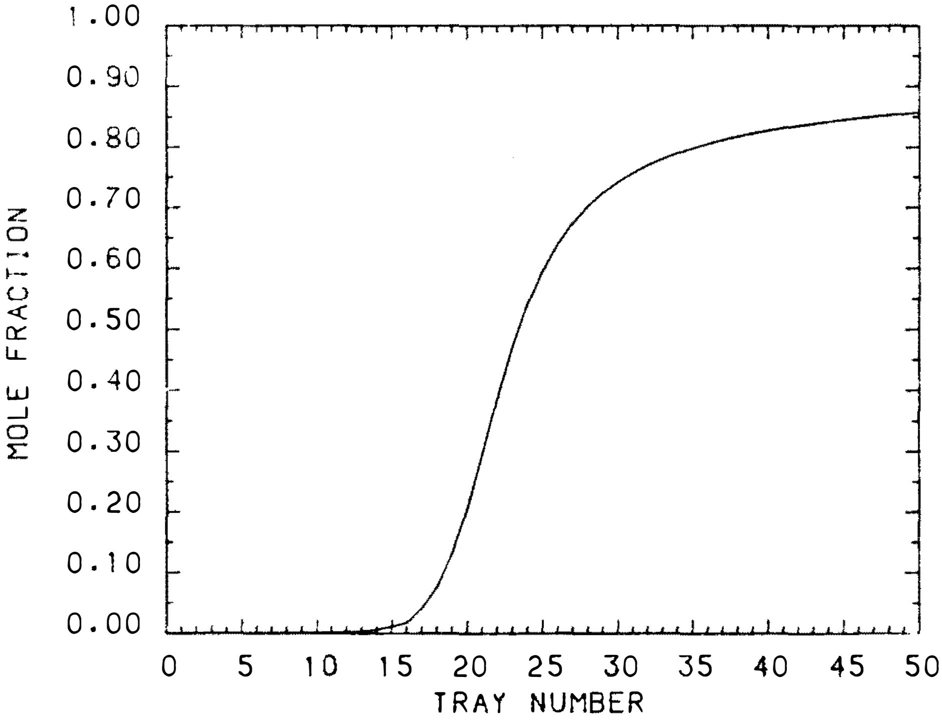

Figure 4.2: Ethanol Composition Profile

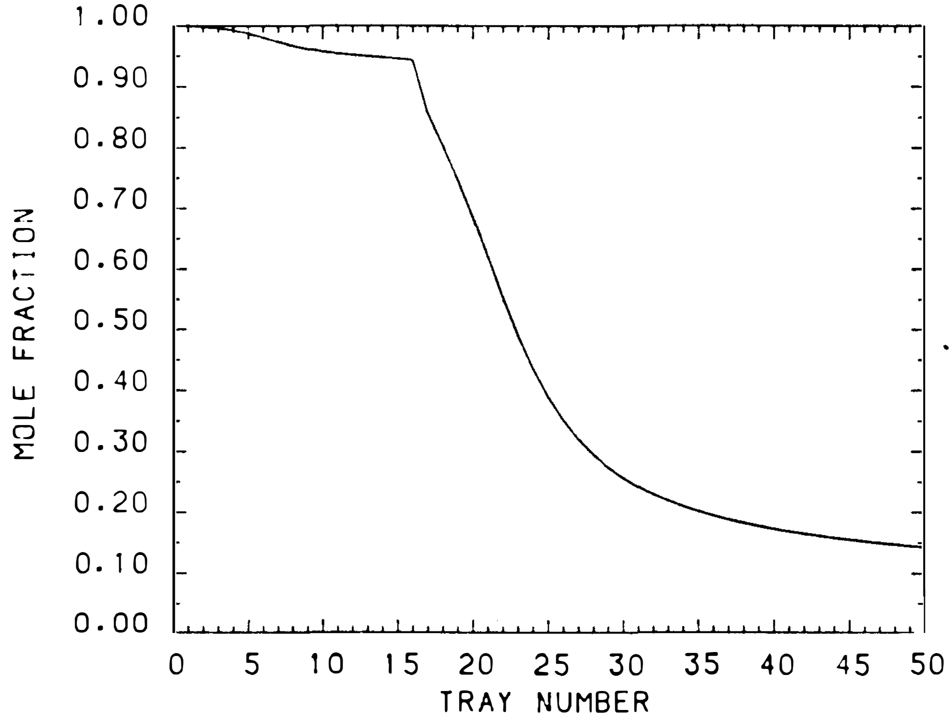

Figure 4.3: Water Composition Profile

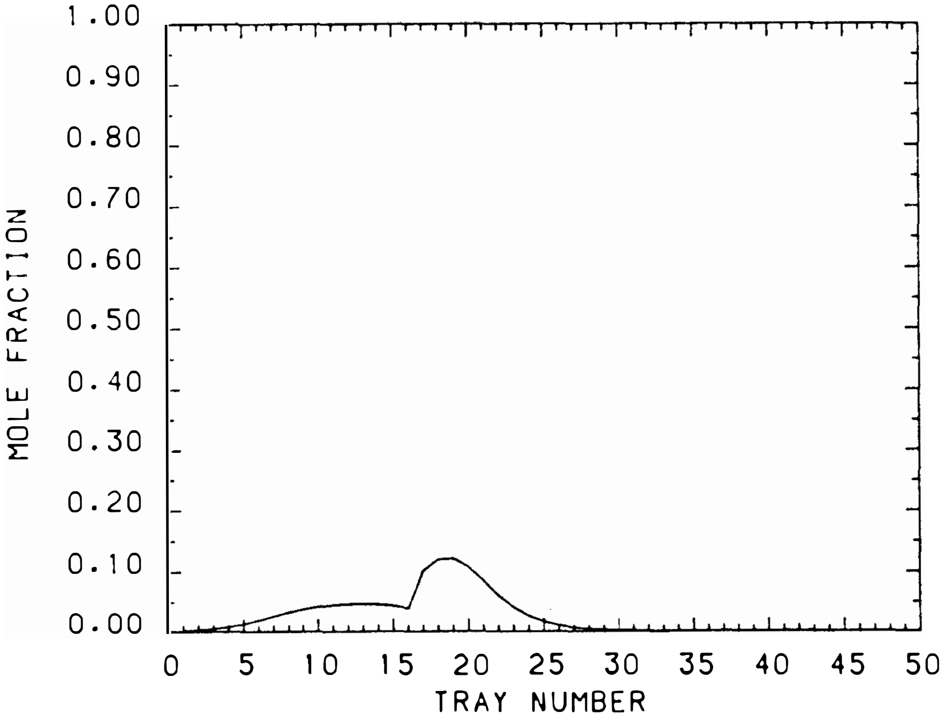

Figure 4.4: Fusel Oil Composition Profile

sidedraw to keep the fusel oils from building up and causing a disturbance in the column operation by moving to other locations.

4.2 Sidedraw Studies

To find the optimum operation of the sidedraw in the column there are two main aspects to be considered. The first aspect is the location of the sidedraw. It must, of course, be in an area of the column where the fusel oil concentration is relatively high. This limits the possibilities to a small section of the column. The second aspect of the sidedraw operation is the flow rate. The flow rate can be optimized so as to takeoff as much of the fusel oils as possible while minimizing the amount of ethanol lost in the sidedraw.

A plot of the fusel oil concentration reveals that the fusel oil concentration is significant only in the range of trays 17–21. In order to determine the "optimum" sidedraw location the sidedraw was moved to different locations over the range stated above. The fusel oil composition was plotted for each of the different sidedraw locations investigated. The optimum sidedraw location is the one which reduces the concentration of the fusel oils in the column but affects the ethanol concentration as little as possible. The peak in the fusel oil profile moves up the column as the sidedraw is located at higher locations as shown in Figure 4.5. The fusel oil concentration also tends to increases at the locations that are higher in the column. However the amount of ethanol that is lost out of the sidedraw increases as the sidedraw is moved up the column,

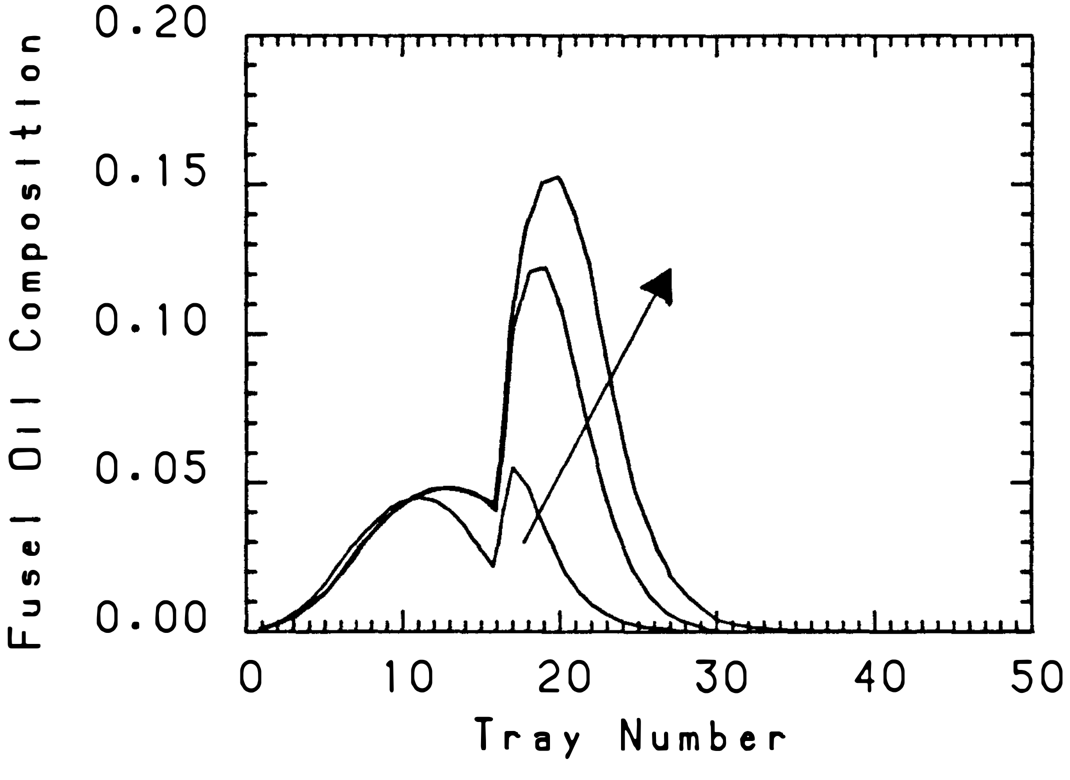

Figure 4.5: Effect of Sidedraw Location on the Fusel Oil Composition Profile

because the ethanol concentration is greater near the top of the column. There is not a significant increase in the performance of the column with a change in the sidedraw location since the increase in fusel oil takeoff is essentially offset by the increase in ethanol takeoff through the sidedraw. Since there is no impetus to move the sidedraw from its original location on tray 18 it will remain at that location.

The sidedraw flow rate can be studied thoroughly once a sidedraw location has been chosen. Figure 4.6 shows that the fusel oil peak concentration increases as the sidedraw flow rate is increased and moves higher up in the column. The flow rates in Figure 4.6 vary from 0.0 to 60.0 lb_{mol}/hr. The peak composition increases linearly with the flow rate up to about $30 lb_{mol}/hr$ then starts to flatten out as shown in Figure 4.7. The peak location moves up the column fairly linearly with respect to the flow rate also, as seen in Figure 4.8. Increasing the flow rate does not greatly increase the amount of fusel oils drawn off but but it does change the optimum sidedraw location. Thus the sidedraw rate should be kept small at the original value of $2.5 lb_{mol}/hr$.

4.3 Energy Study

The main objective of any chemical process is to make money. A distillation column can be operated at several different states. Some operating conditions are more economical than others, and some could even lose money. To determine the "optimum" operating conditions, from a financial viewpoint,

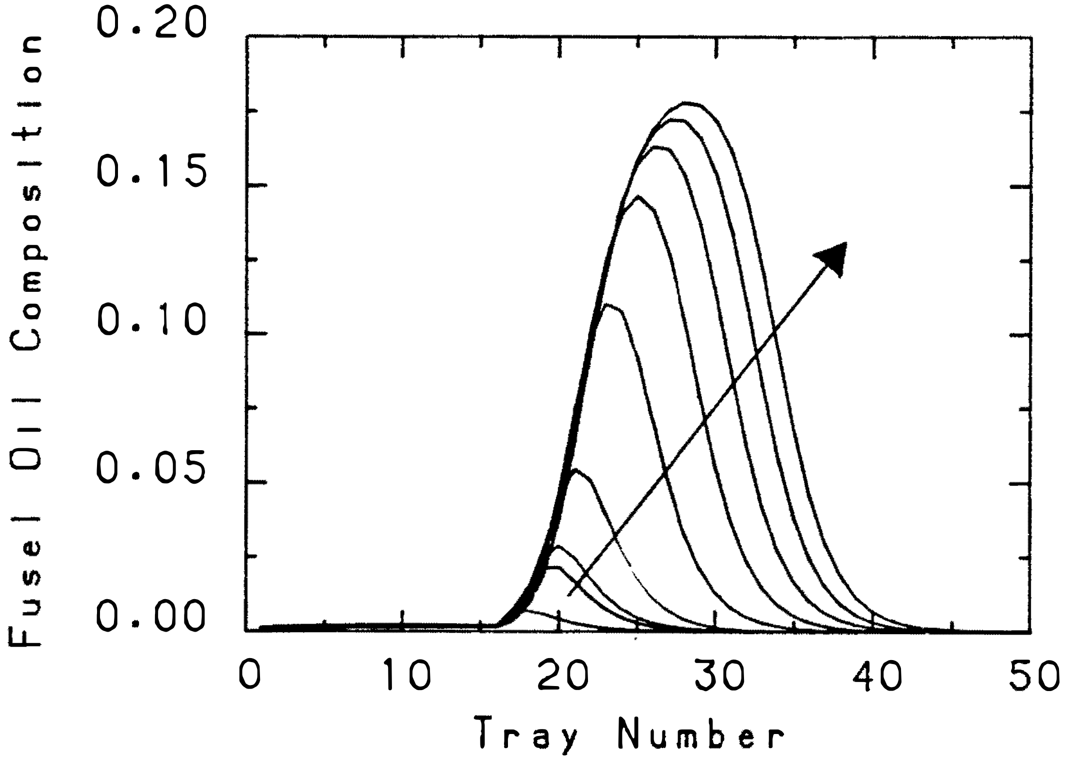

Figure 4.6: Effect of Sidedraw Rate on the Fusel Oil Composition Profile

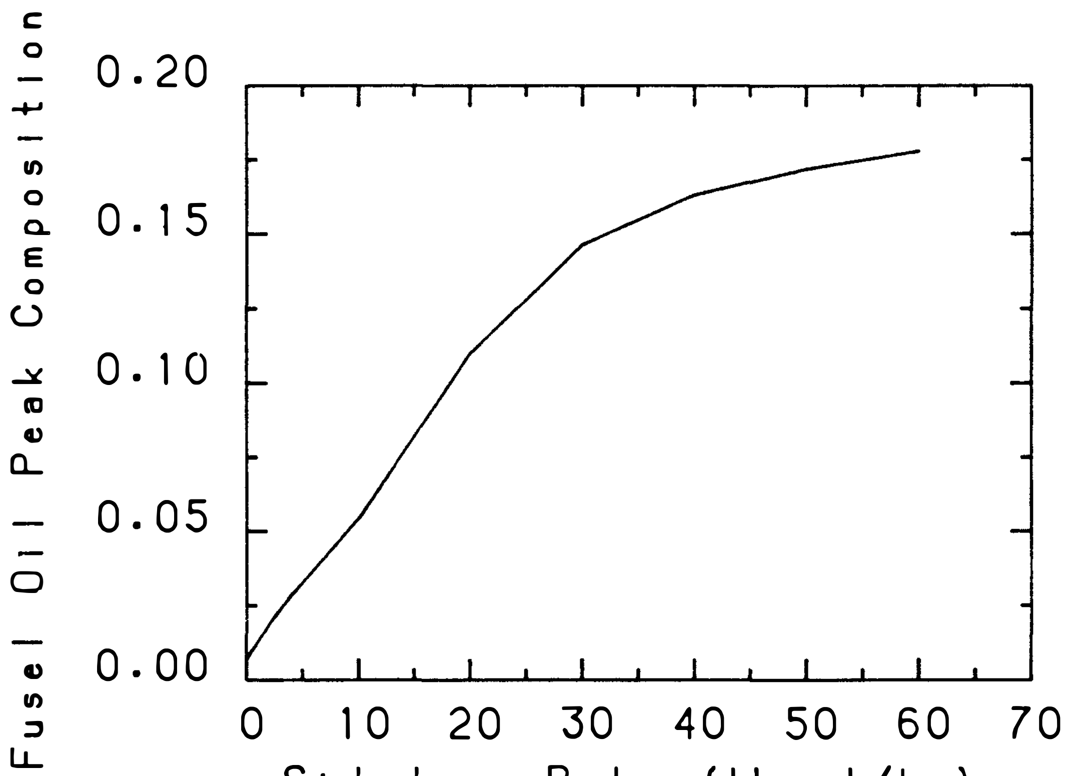

Figure 4.7: Effect of Sidedraw Rate on the Fusel Oil Peak Composition

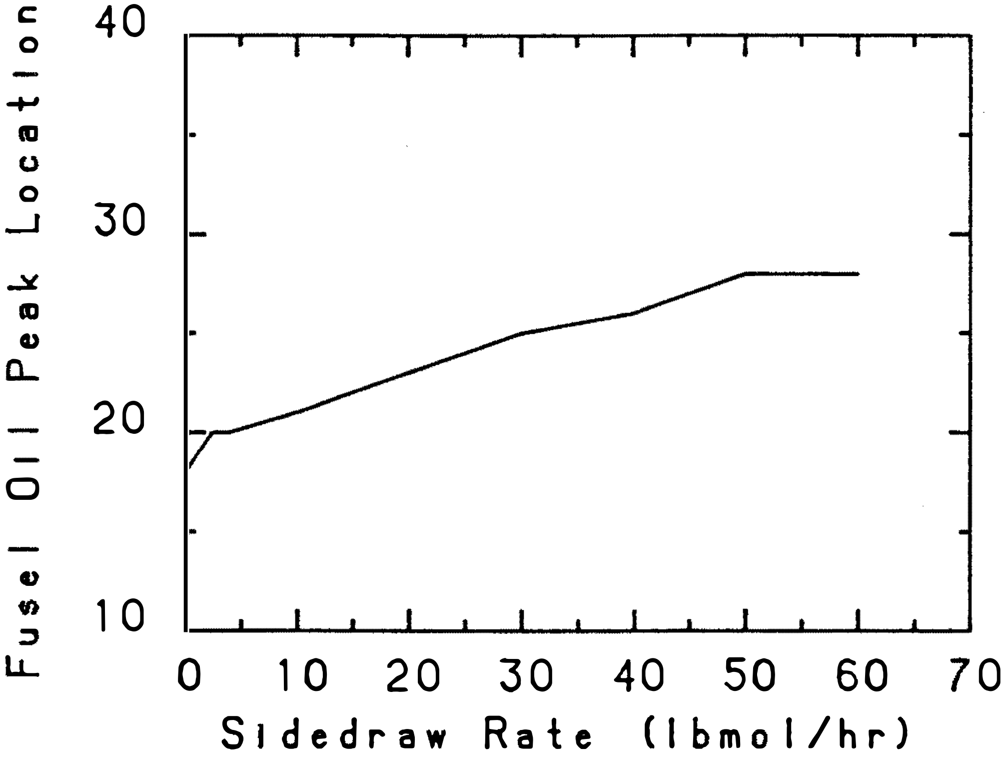

Figure 4.8: Effect of Sidedraw Rate on the Fusel Oil Peak Location

the amount of steam needed to recover a certain amount of ethanol is recorded for several different conditions.

For the purposes of this study the cost of steam is assumed to be the major variable cost in the operation of the column. The cost of steam used for this study is \$3.60/1000 lbm of steam and the value of ethanol was taken to be \$1.50/gal. Multiplying these values by the flow rates of steam and ethanol in the distillate the total cost and total value. These values are plotted against the ethanol distillate flow rate in Figure 4.9. From this figure it appears that there is always a large profit margin. This can be deceiving, a plot of the derivatives of these two lines versus the same x-axis as before yields an interesting aspect.

Referring to Figure 4.10, the slope of the "value line" is constant, Which means that the value per lb-mole of the product is constant at \$10.32/lb-mole. The "cost line" however has a rapid increase after 18.125 lb-moles of ethanol, this indicates that the steam cost per lb-mole of product increases dramatically at the point mentioned. It should be noted that the cost/value per lb-mole of steam/ethanol is not crucially important in this study, different values would just shift the lines in Figure 4.10 up or down. The "cutoff point" will remain in approximately the same location because of the rapid increase in the slope of the cost line. This study shows that the column would be operated most economically below 18.125 lb-moles of ethanol in the distillate stream.

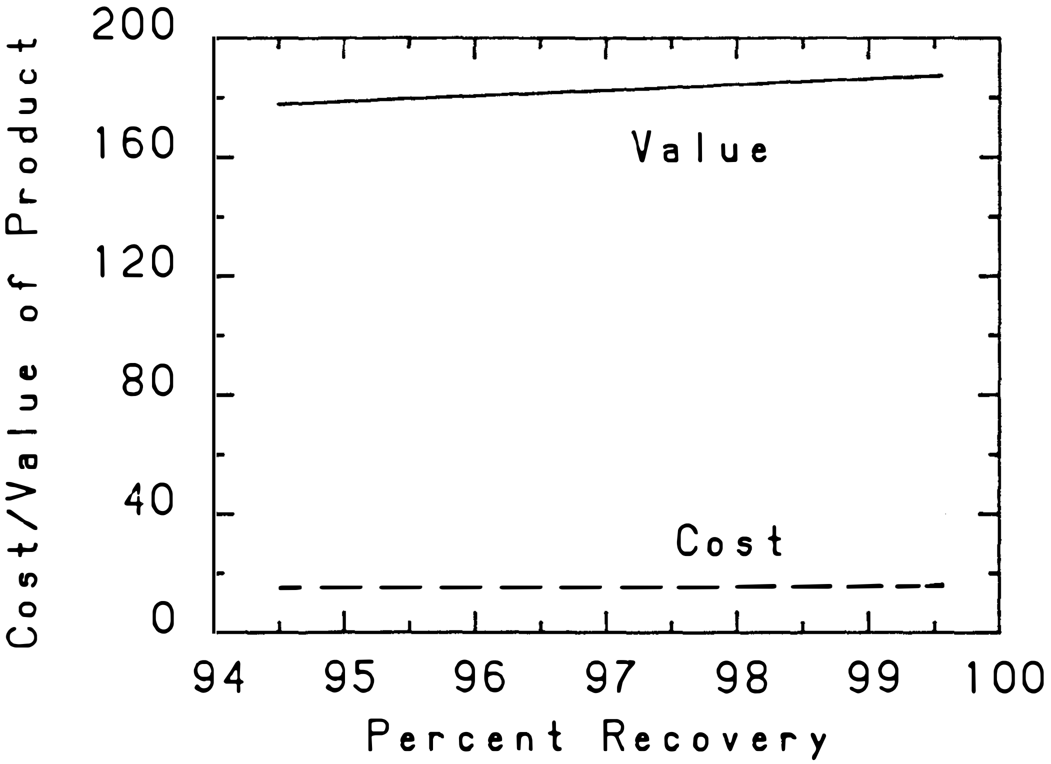

Figure 4.9: Energy Cost for Increasing Percent Recovery

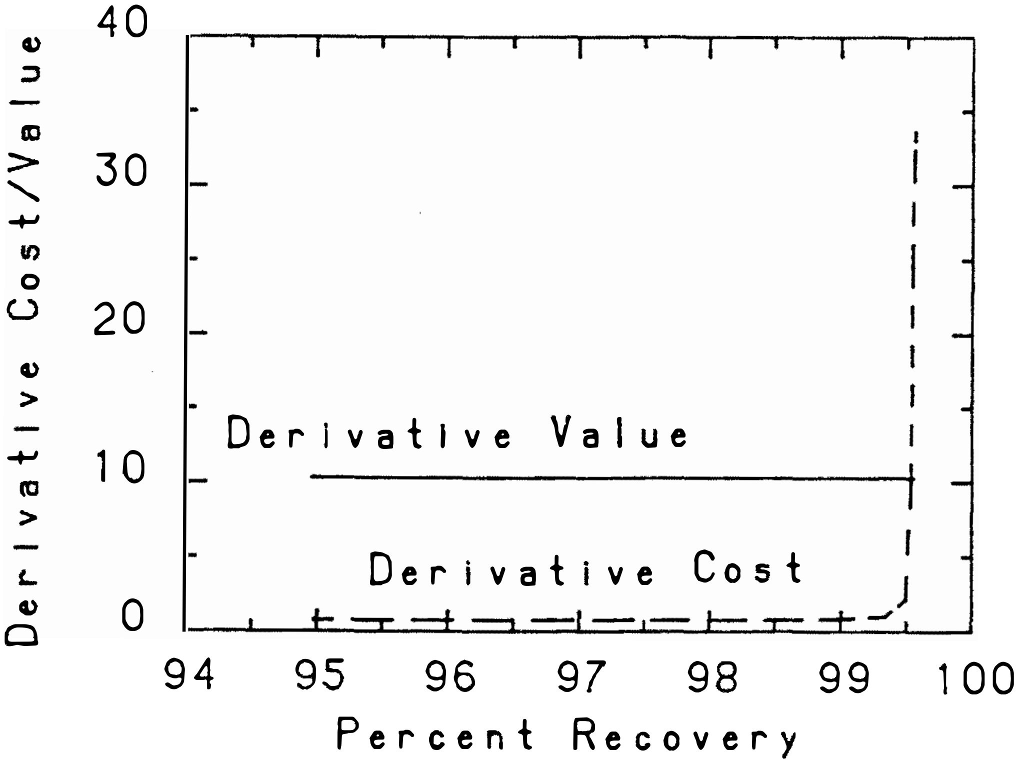

Figure 4.10: Derivative Energy Cost for Increasing Percent Recovery

4.4 Double Precision

During the course of this research the percentage disturbance used to calculate the gains was decreased from 1% to .01% to closer approximate the derivative and reduce the affect of nonlinearities. As this was done it was noticed that the SVD analysis changed markedly while the gains did not change significantly. The only noticeable change was that some of small nonzero values become zero at the new disturbance value. These zeros were the cause of the changes in the SVD analysis. To alleviate this problem a double precision version of the program was created. As the percentage disturbance was decreased in this new version the gains and SVD analysis did not noticeably change. This illustrates the need for increased precision in the calculation of the gains. The use of double precision does not significantly increase the computation time needed and is therefore used for all of the real variables in the simulation.

CHAPTER 5

CONTROL ANALYSIS

5.1 Sensitivity Studies

One of the first things to look at in determining the control scheme for a distillation column is the sensitivity of the column to the manipulated variables. The easiest method of determining changes in the column operation is by looking at the temperature profile. Varying the manipulated variable from the base case +5% and +10% and plotting the temperature profiles on the same axes will result in a good indication of the sensitivity of the column to the manipulated variables.

The BR method was investigated in Figures 5.1 and 5.2. Neither the bottoms flow or the reflux ratio has much of an effect on the temperature profile. The same is true for changes in the reboiler duty and reflux ratio in the QR scheme as shown in Figures 5.3 and 5.4. The DQ method shown in Figures 5.5 and 5.6 causes little effect with the distillate rate but the reboiler duty has a significant effect on the temperature profile. The reflux rate has little effect in the LB scheme where the bottoms rate take the column to a new steady state (see Figures 5.7 and 5.8). Both variables in the LQ scheme have significant effects on the temperature profile in Figures 5.9 and 5.10.

The BR and QR schemes do not appear to be good control schemes

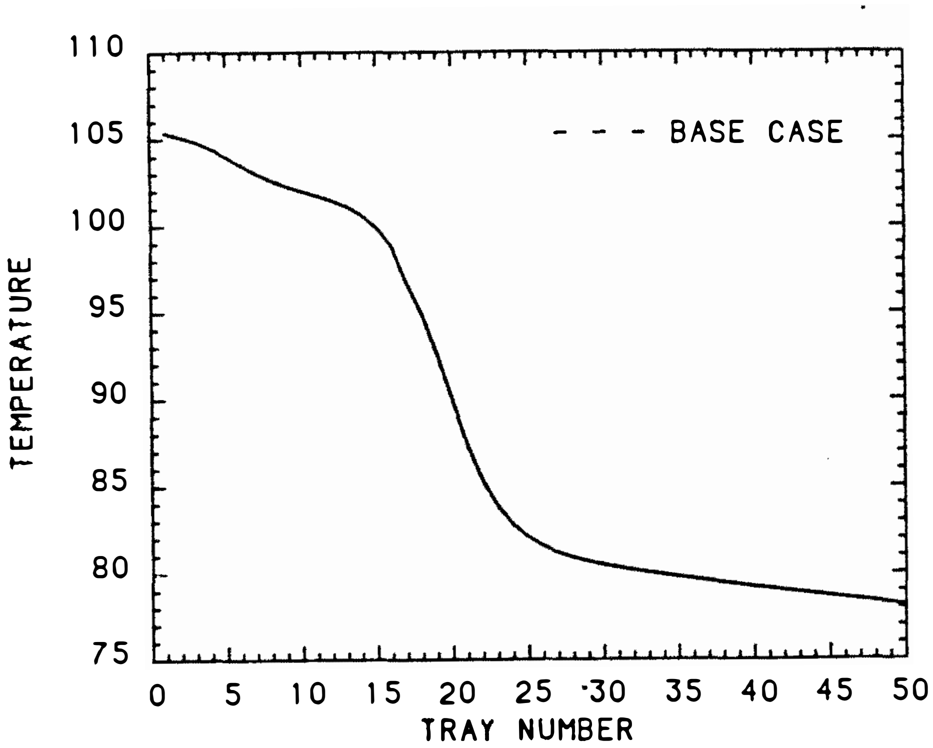

Figure 5.1: Sensitivity Plot for BR scheme — Bottoms Rate

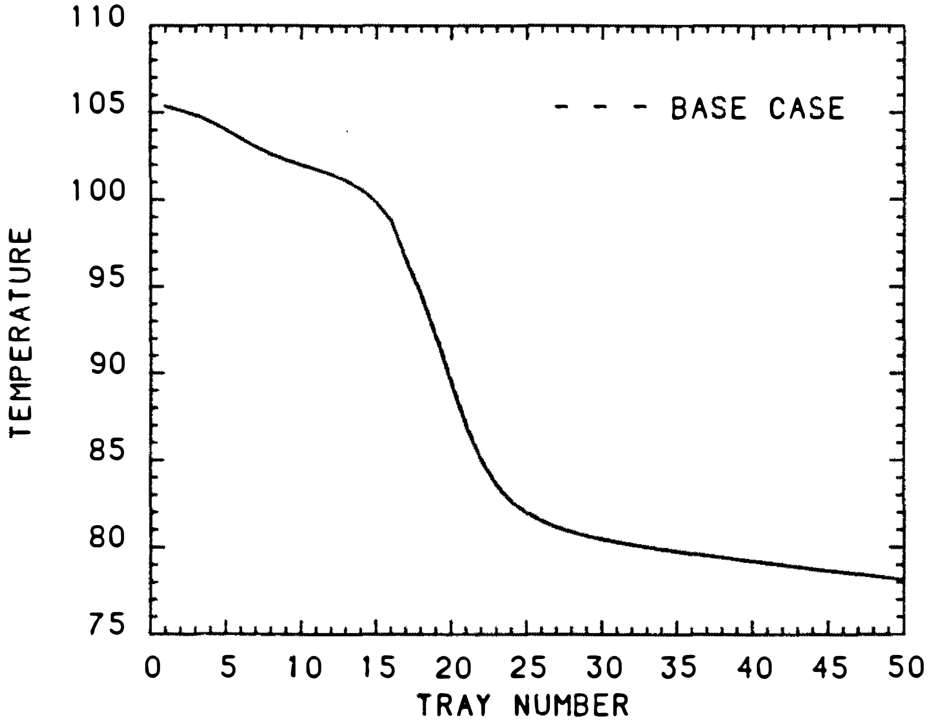

Figure 5.2: Sensitivity Plot for BR scheme — Reflux Ratio

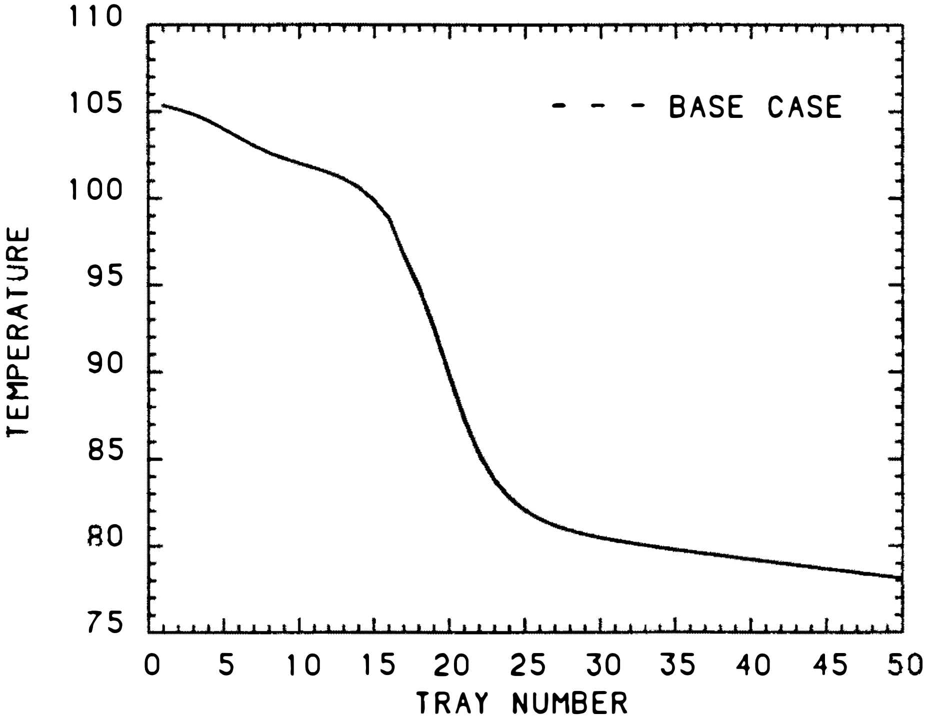

Figure 5.3: Sensitivity Plot for QR scheme — Reboiler Duty

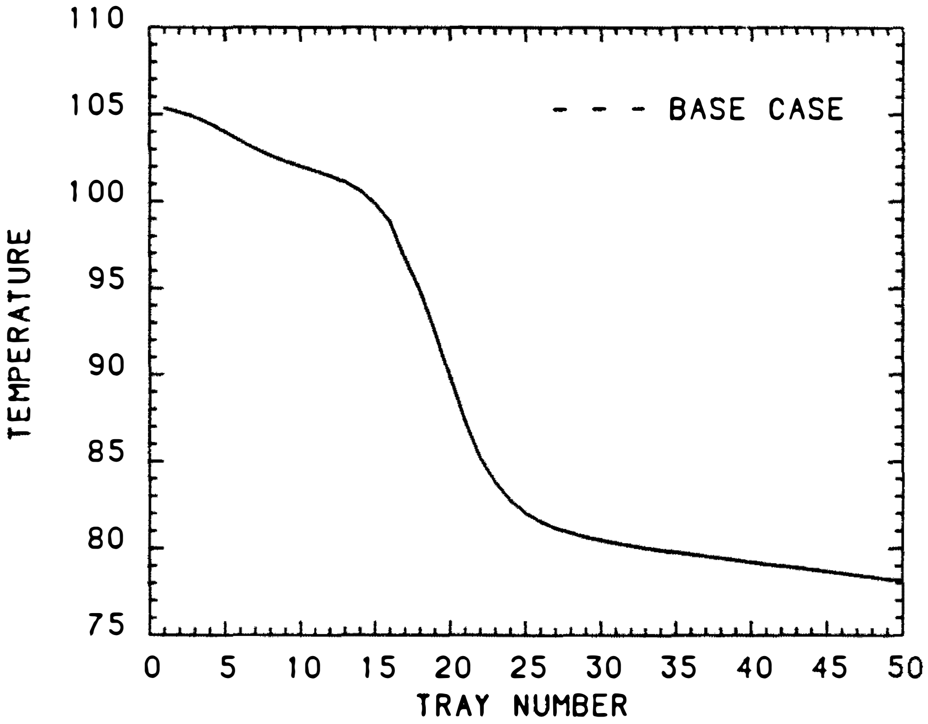

Figure 5.4: Sensitivity Plot for QR scheme — Reflux Ratio

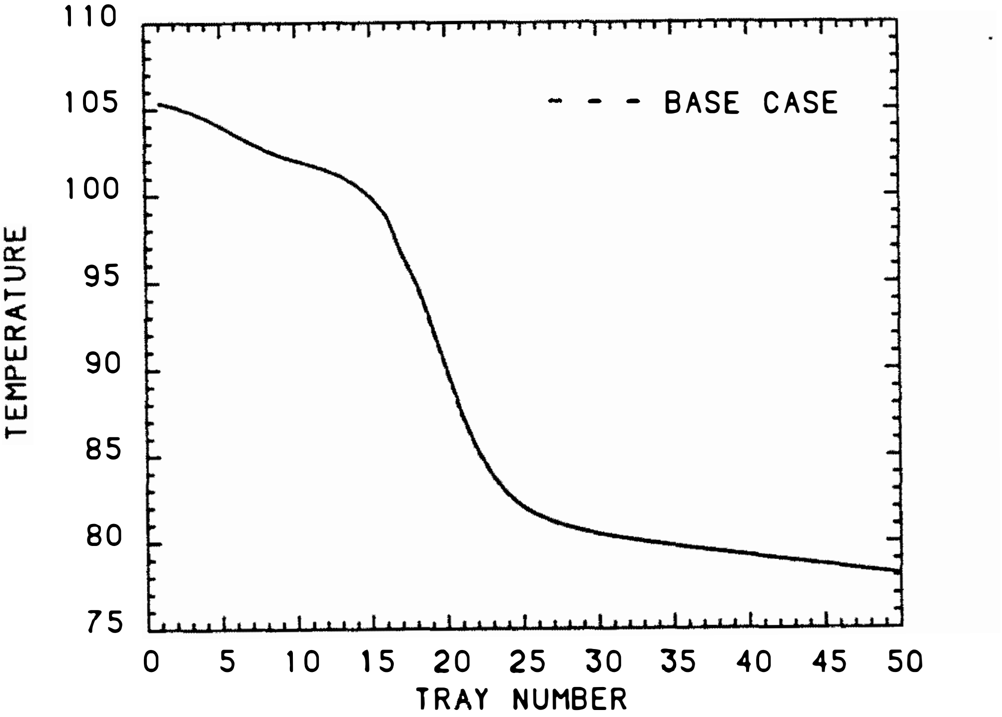

Figure 5.5: Sensitivity Plot for DQ scheme — Distillate Rate

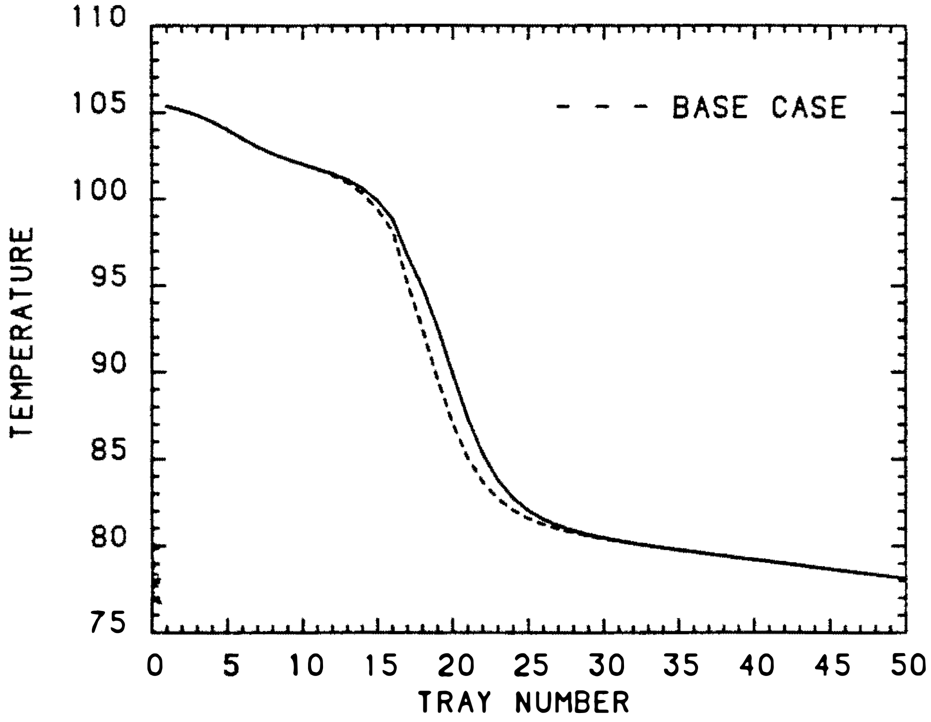

Figure 5.6: Sensitivity Plot for DQ scheme — Reboiler Duty

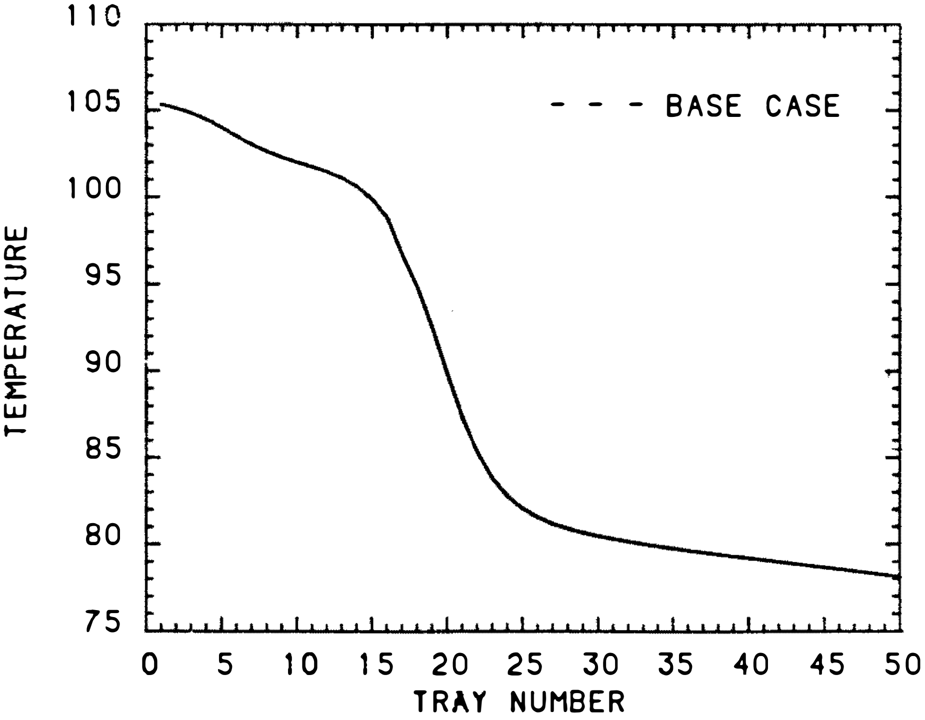

Figure 5.7: Sensitivity Plot for LB scheme — Reflux Rate

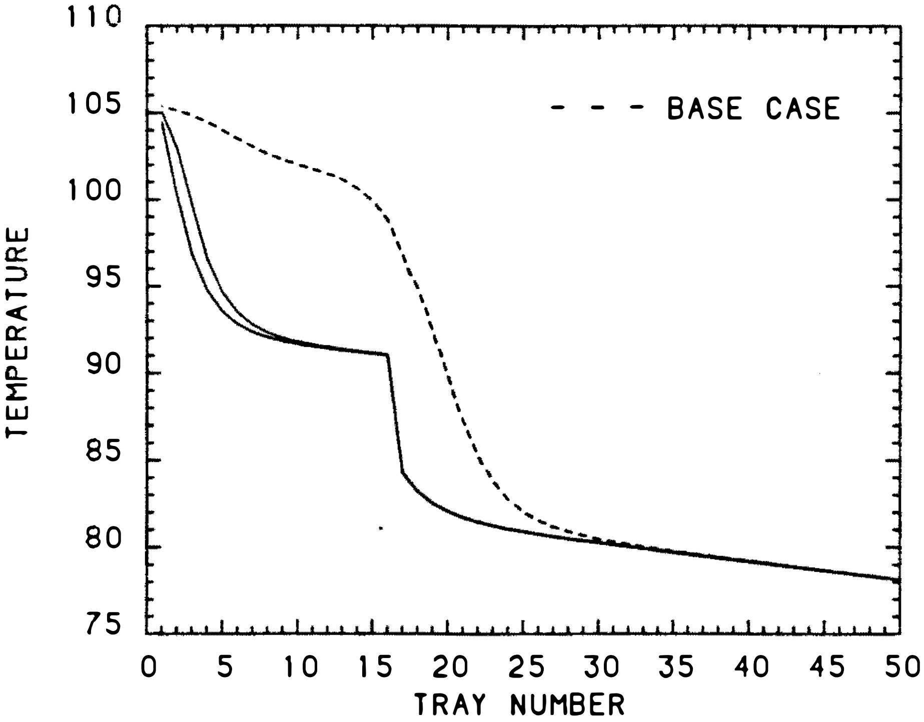

Figure 5.8: Sensitivity Plot for LB scheme — Bottoms Rate

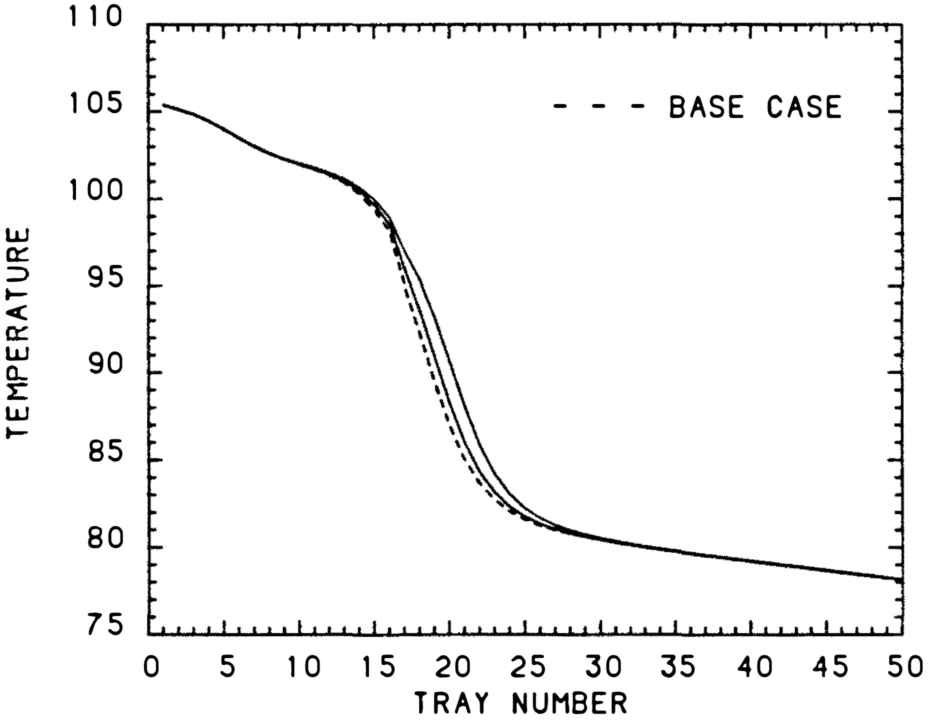

Figure 5.9: Sensitivity Plot for LQ scheme — Reflux Rate

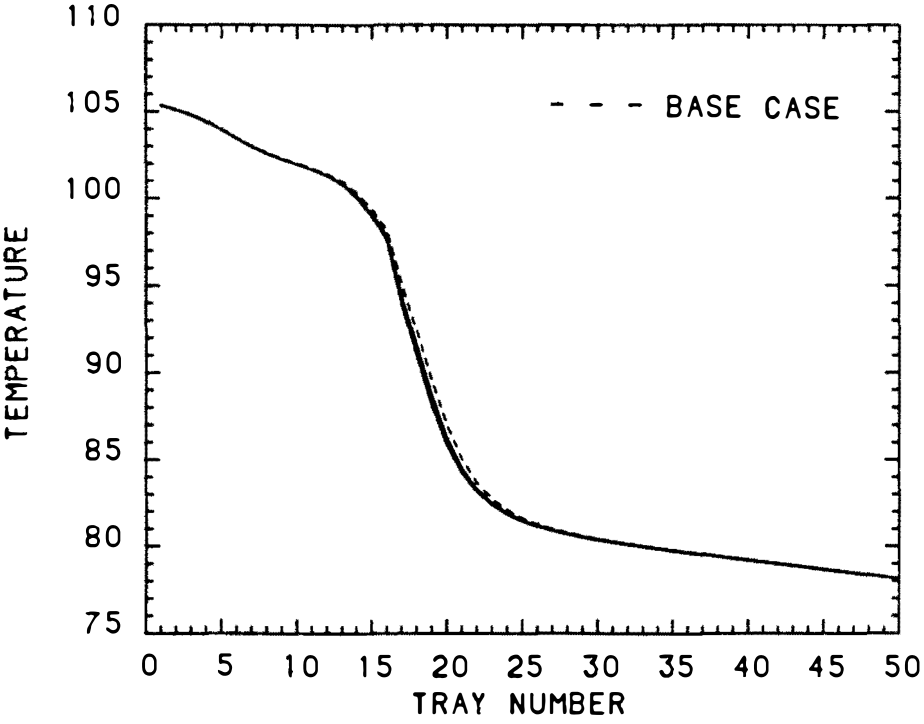

Figure 5.10: Sensitivity Plot for LQ scheme — Reboiler Duty

according to this study since the column is not sensitive to changes in the manipulated variables. The LB scheme appears to be a bad choice because of the extreme sensitivity of the temperature profile to changes in the bottoms rate. However it should be noted that a relatively small change in the bottoms rate is a large change in the distillate rate and can be expected to have a large effect on the system. The DQ and LQ schemes seem to be the most likely candidates according to this study.

5.2 Base Case SVD Studies

Once a base case operating condition was established, the SVD was performed on the temperature gains. The gains were scaled as discussed earlier by dividing by the base case value for the particular valve or sensor. The SVD analysis for the base case on all five of the first level control schemes are summarized in Table 5.1. Three of the schemes (BR, DQ and LB) have condition numbers (κ) under 100 which indicates a fairly good possibility of dual-ended control. The QR scheme has a κ of 180 which is not very likely for dual-ended control. The LQ control scheme with a condition number of 1,322 is essentially one dimensional in terms of the directions that the column can be moved by the scheme. The DQ scheme looks to be the most promising since it has the lowest condition number. Note that the BR and LB schemes have similar κ's and σ's which is as should be expected because the two control schemes are very similar.

Table 5.1: SVD Analysis for Temperature Gains

Method	Condition No.	Singular Values	
BR	97	8.10×10^{-2}	8.37×10^{-4}
QR	180	1.24×10^{-1}	6.90×10^{-4}
DQ	66	8.12×10^{-2}	1.22×10^{-3}
LB	97	8.12×10^{-2}	8.36×10^{-4}
LQ	1,322	9.10×10^{-1}	6.89×10^{-4}

It is also possible to use the sidedraw as a manipulated variable to control the column. The SVD analysis of these control schemes is summarized in Table 5.2. All five schemes have κ's over 100. The same general trends are still prevalent in that the DQS scheme has the smallest κ while that for the LQS scheme is extremely large. The third singular value ,σ_3, is very small and similar for each of the five schemes. This is expected since the sidedraw flow rate is very small in comparison to the other flows and since the third singular value is an indication of the sensitivity to that manipulated variable. None of these schemes will be further considered for controlling the column because of the large κ's. Even if the κ's had been good the sidedraw was not a very likely candidate for controlling the column. The flow rate is so small that the amount of time for changes in the sidedraw to take effect would be too large.

Table 5.2: SVD Analysis with the Sidedraw as a Manipulated Variable

Method	Condition No.	Singular Values		
BRS	908	1.04	2.11×10^{-3}	1.14×10^{-3}
QRS	4,350	4.98	6.58×10^{-3}	1.14×10^{-3}
DQS	845	1.02	3.10×10^{-3}	1.21×10^{-3}
LBS	5,450	6.02	1.35×10^{-2}	1.10×10^{-3}
LQS	106,000	119	1.12×10^{-1}	1.13×10^{-3}

5.3 Sensor Location

5.3.1 Principal Component Method

A commonly used method for sensor location that uses information from the SVD analysis is the principal component method. This method uses the **U** matrix of the SVD to determine the best sensor location. The trays corresponding to the **U** matrix components with the largest magnitude are the trays that are the most sensitive to changes in the associated manipulated variable and therefore should be good sensors.

There are cases where the maximums may be located very close to each other. This would result in considerable interaction between the two control loops. The most desirable sensor would be very sensitive to changes in only one manipulated variable while being fairly insensitive to the remaining manipulated variable(s). For this reason it is occasionally necessary to shift the sensors to different location than those determined by the maximums. It is helpful for this analysis to plot the columns of the **U** matrix (**U** vectors). The **U** vector plots make it considerably easier to see the relationship between sensor sensitivity and sensor interaction.

A **U** vector plot for the DQ control scheme of the ethanol-water column is shown in Figure 5.11. The $\mathbf{U}_1$ vector, which is associated with the distillate flow rate, has a maximum magnitude at tray 18. The $\mathbf{U}_2$ vector, associated with the reboiler duty, gives tray 13 as its temperature sensor. This results in the following controller pairing.

$$T_{18} \rightarrow \text{Distillate flow rate (D)}$$

$$T_{13} \rightarrow \text{Reboiler Duty (Q)}$$

After the temperature sensors (13 and 18) were selected the following 2×2 gain matrix of the two trays temperatures with respect to the manipulated variables (D and Q) was found.

$$\mathbf{K} = \begin{bmatrix} 4.98\times10^{-2} & -1.99\times10^{-4} \\ 2.91\times10^{-3} & 5.04\times10^{-4} \end{bmatrix}$$

An SVD analysis of this steady-state gain matrix gives the following **U** and **V** matrices and singular values.

$$\mathbf{U} = \begin{bmatrix} -9.98\times10^{-1} & -5.84\times10^{-2} \\ -5.84\times10^{-2} & 9.98\times10^{-1} \end{bmatrix}$$

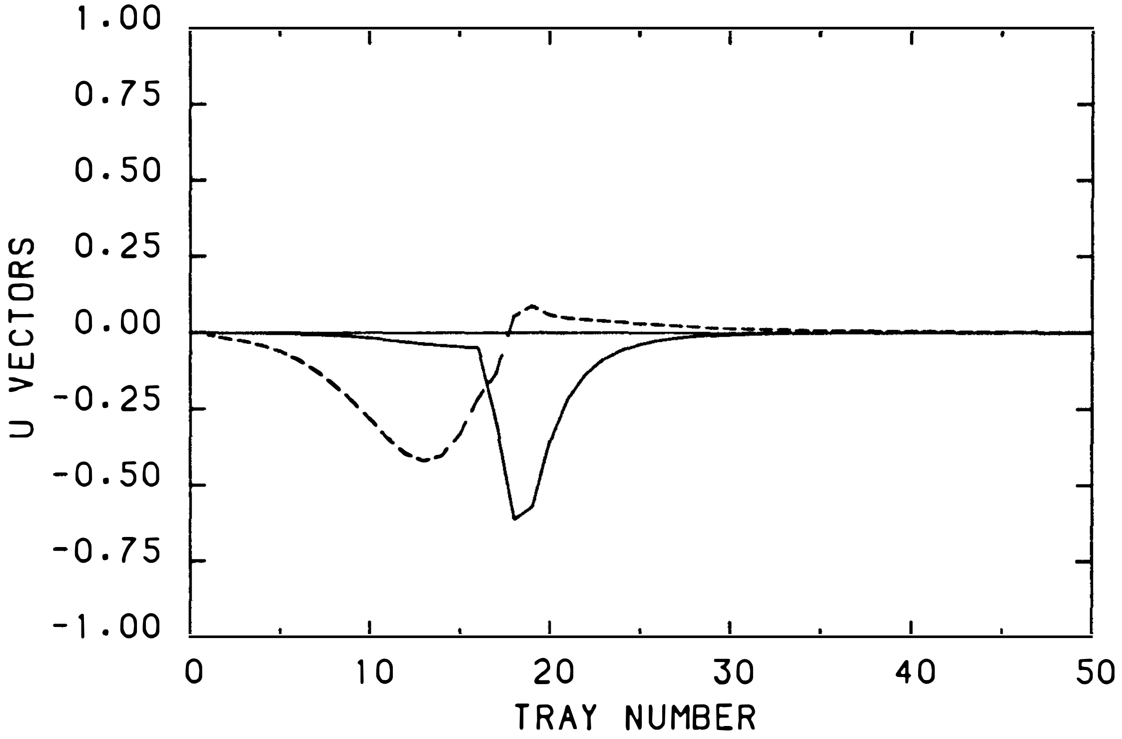

Figure 5.11: **U** Vector Plot for DQ Method

Table 5.3: Partial SVD Analysis for Temperature Gains

Method	Sensors	Condition No.	Singular Values		RGA(1,1)
BR	18 - 13	141	4.97×10^{-2}	3.53×10^{-4}	0.974
QR	18 - 13	261	7.61×10^{-2}	2.91×10^{-4}	-7.110
DQ	18 - 13	97	4.98×10^{-2}	5.15×10^{-3}	0.977
LB	18 - 13	141	4.98×10^{-2}	3.52×10^{-4}	0.977
LQ	18 - 13	1,920	5.59×10^{-1}	2.91×10^{-4}	53.3

$$\mathbf{V} = \begin{bmatrix} -9.99\times10^{-1} & 3.40\times10^{-3} \\ 3.40\times10^{-3} & 9.99\times10^{-1} \end{bmatrix}$$

$$\sigma_1 = 4.98\times10^{-2}$$

$$\sigma_2 = 5.15\times10^{-4}$$

The condition number of 97 is of approximately the same magnitude as the overall κ. If this had not been true then the trays selected for sensors would not have been good choices. The **U** and **V** matrices indicate that the pairing indicated by the overall SVD analysis was correct. The RGA λ for this partial analysis is 0.977 as can be seen in Table 5.3.

This same analysis was performed on each of the five first level control schemes. For each of the control schemes the same two sensors (18 and 13) were selected by the principal component method (see Table 5.3). The partial SVD condition numbers are of the same magnitude and the **U** and **V** matrices confirm the results of the overall SVD analysis. The QR and LQ schemes which have the highest condition number also have bad λ's of -7.110 and 53.3 respectively. Thus the RGA confirms the SVD in that these are not very very good control schemes for this particular column.

5.3.2 Modified Principal Component Method

There are times when the principal component is not as straightforward as it is in the DQ scheme for the ethanol-water column. In an attempt to eliminate the heuristic aspect involved in the adjusting of the principal component method for the interaction between sensors a modification has been made for an $m \times 2$ study. Instead of plotting the **U** vectors, the difference between the magnitudes of $\mathbf{U}_1$ and $\mathbf{U}_2$ are plotted. The positive maximum corresponds to the tray should be chosen as the sensor for the $\mathbf{U}_1$ manipulated variable. The $\mathbf{U}_2$ manipulated variable should be paired with the tray where the largest negative value occurs. Studying the DQ scheme in this manner gives the same sensors as chosen by the principal component method but it is much more straightforward (see Figure 5.12). There is no difference in the sensor location for any of the five first level control schemes. The modified principal component is an improvement over the principal component method in that it does not depend on the experience of the user to move the sensors in order to decrease the interaction.

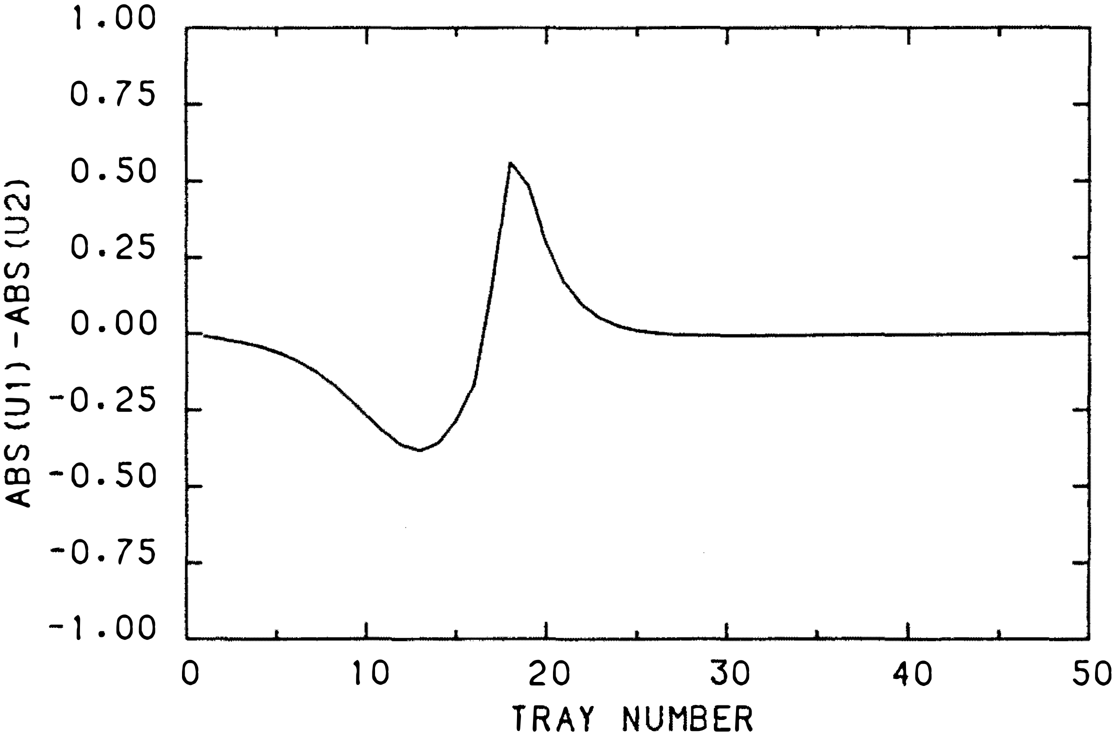

Figure 5.12: Modified Principal Component Plot for DQ Scheme

5.3.3 Global Search Methods

5.3.3.1 Condition Number

At times the condition number for the partial SVD analysis is the smaller than the overall condition number. For the loop pairings with only a single temperature measurement, the partial SVD is more representative of what the control system must deal with. Because of this, a global search of all of the 2×2 subsystems for the minimum condition number was made. It was hoped that this would give temperature sensors that result in a well-conditioned control system. Since all 2×2 subsystems will be investigated, the RGA may also be calculated for each of the 1225 subsystems. This will allow for a comparison of the κ search with the results of the RGA.

A 3-D plot of the inverse condition number versus the tray locations is shown in Figure 5.13. The inverse of the condition number ($1/\kappa$) is plotted so that all of the values would be less than or equal to one. The peak in this plot occurs at trays 1 and 44. It is understandable that these locations have low κ's because they are at opposite ends of the column and therefore don't interact to a very high degree. These locations and those nearby all have fairly low κ's but they are in very insensitive sections of the column and would therefore not be good choices for control. A summary of the twenty pairs with the lowest condition numbers is located in Table 5.4

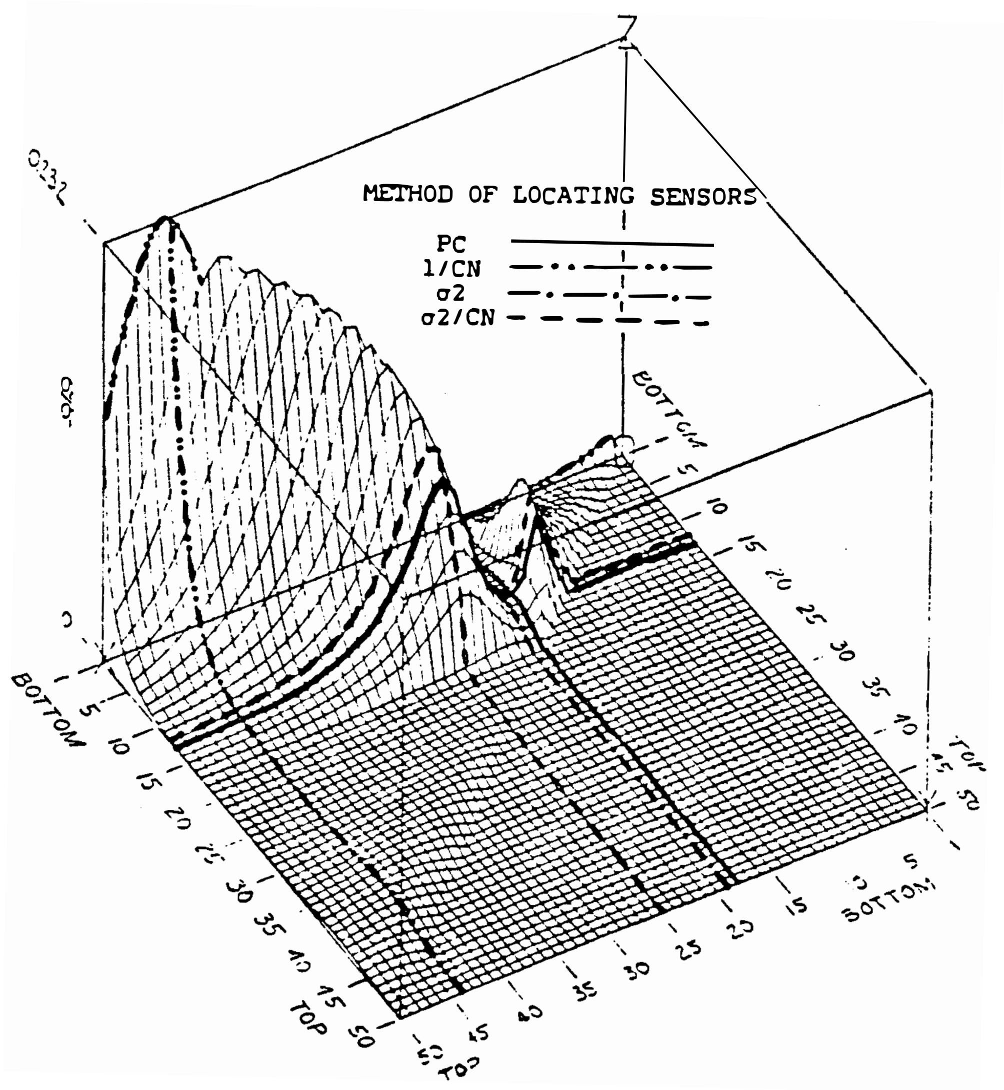

Figure 5.13: Condition Number Plot for DQ Scheme

Table 5.4: Minimum Condition Number Search for DQ Method

First Sensor	Second Sensor	Condition Number	Singular Values		Intersivity
			$\sigma_1 \times 10^3$	$\sigma_2 \times 10^4$	$\Xi \times 10^4$
44	1	4.30	4.38	10.2	2.36
45	1	4.30	4.00	9.28	2.15
43	1	4.47	4.88	10.9	2.44
46	1	4.48	3.71	8.29	1.85
42	1	4.81	5.53	11.5	2.39
47	1	4.85	3.51	7.25	1.50
40	2	4.87	10.0	20.5	4.20
39	2	4.92	11.0	22.3	4.53
41	2	5.01	9.28	18.5	3.69
38	3	5.12	15.1	29.5	5.75
37	3	5.12	16.6	32.3	6.31
38	2	5.17	12.3	23.8	4.61
35	4	5.32	25.0	47.0	8.83
36	4	5.32	22.6	42.5	7.99
39	3	5.32	14.0	26.4	4.95
41	1	5.33	6.37	11.9	2.24
42	2	5.34	8.76	16.4	3.07
36	3	5.35	18.6	34.8	6.51
48	1	5.43	3.37	6.21	1.14
34	5	5.51	34.1	61.8	11.2

5.3.3.2 Lowest Singular Value

In order to find the most sensitive pair of sensors a plot of the smallest singular value (σ_2) versus the tray locations was made (see Figure 5.14). The σ_2 value is an indication of the sensitivity of the associated sensor to its manipulated variable. The peak in Figure 5.14 occurs at trays 13 and 19. This selection is consistent with the one indicated by the principal component method. The sensitivity is at a maximum in this area but the interaction is rather high ($\kappa = 89.9$). The fact that the sensitive trays have high κ's can be more easily seen in Table 5.5.

5.3.3.3 Intersivity Index

In order to address both the sensor interaction (κ) and the sensor sensitivity (σ_2) a new index was created. The intersivity index (Ξ) is merely the ratio of the smallest singular value to the condition number.

$$\Xi = \frac{\sigma_2}{\kappa} = \frac{\sigma_2^2}{\sigma_1}$$

The smallest singular value represents sensitivity of the weakest part of the system and should be kept large. The condition number indicates the level of interaction between sensors and ideally should be small. A large intersivity index indicates the system has low interaction and high sensitivity. Plotting this new index against the tray number in the same manner as previously performed on $1/\kappa$ and σ_2. The peak on this plot is located at trays 12 and 25 (see Figure 5.15). The sensor locations obtained from the previous selection

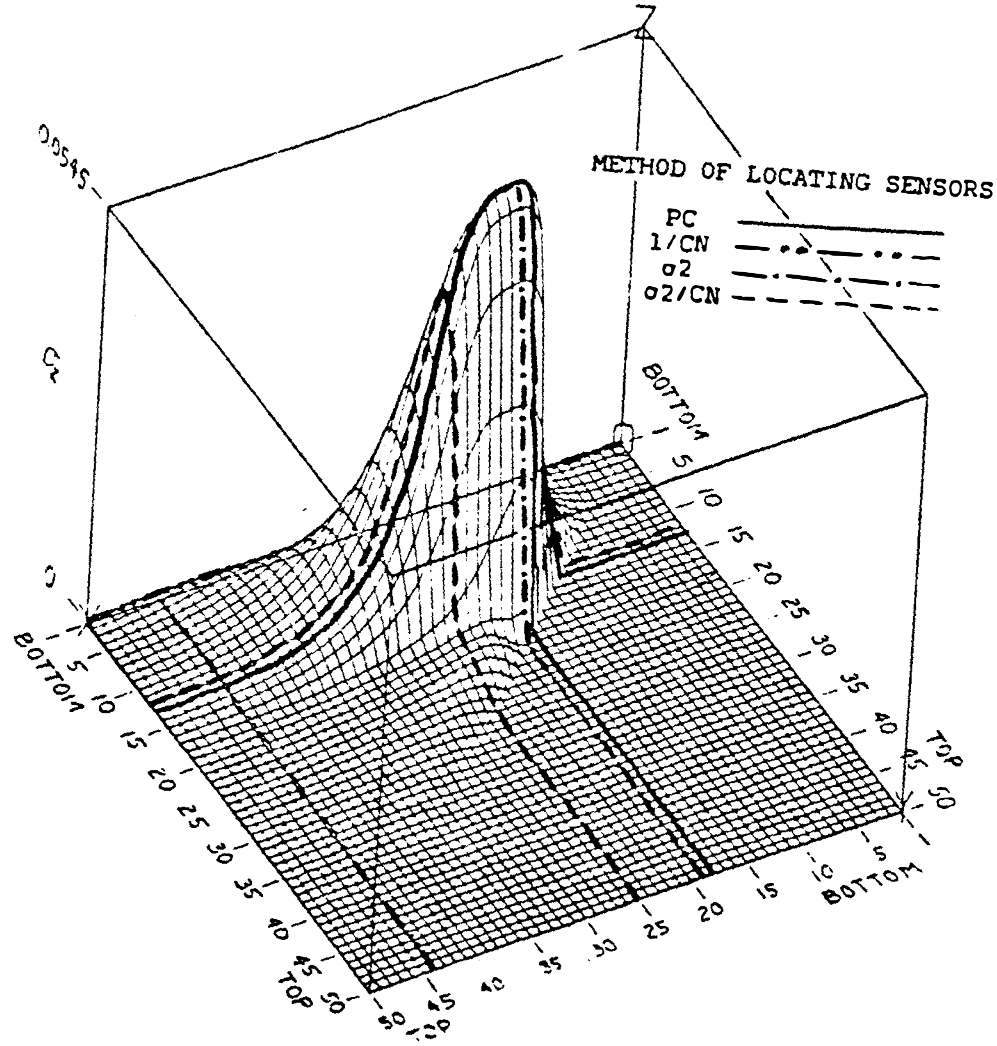

Figure 5.14: Lowest Singular Value Plot for DQ Scheme

Table 5.5: Maximum Singular Value Search for DQ Method

First Sensor	Second Sensor	Condition Number	Singular Values		Intersivity
			σ_1	$\sigma_2 \times 10^2$	$\Xi \times 10^4$
19	13	89.9	4.90	5.45	6.06
20	13	56.0	3.05	5.44	9.70
18	13	96.8	5.25	5.42	5.60
21	13	34.5	1.87	5.42	15.7
22	13	22.3	1.19	5.35	23.9
19	14	93.7	4.90	5.23	5.58
20	14	58.6	3.05	5.21	8.90
18	14	101	5.25	5.20	5.14
21	14	36.2	1.88	5.18	14.3
23	13	15.5	0.80	5.16	33.2
17	13	48.5	2.49	5.13	10.6
19	12	95.4	4.90	5.13	5.38
20	12	59.4	3.04	5.12	8.63
21	12	36.3	1.86	5.12	14.1
18	12	103	5.25	5.11	4.97
22	14	23.7	1.21	5.09	21.4
22	12	23.2	1.18	5.08	21.9
23	12	15.7	0.78	4.97	31.6
17	12	50.9	2.48	4.88	9.59
17	14	51.4	2.50	4.86	9.46

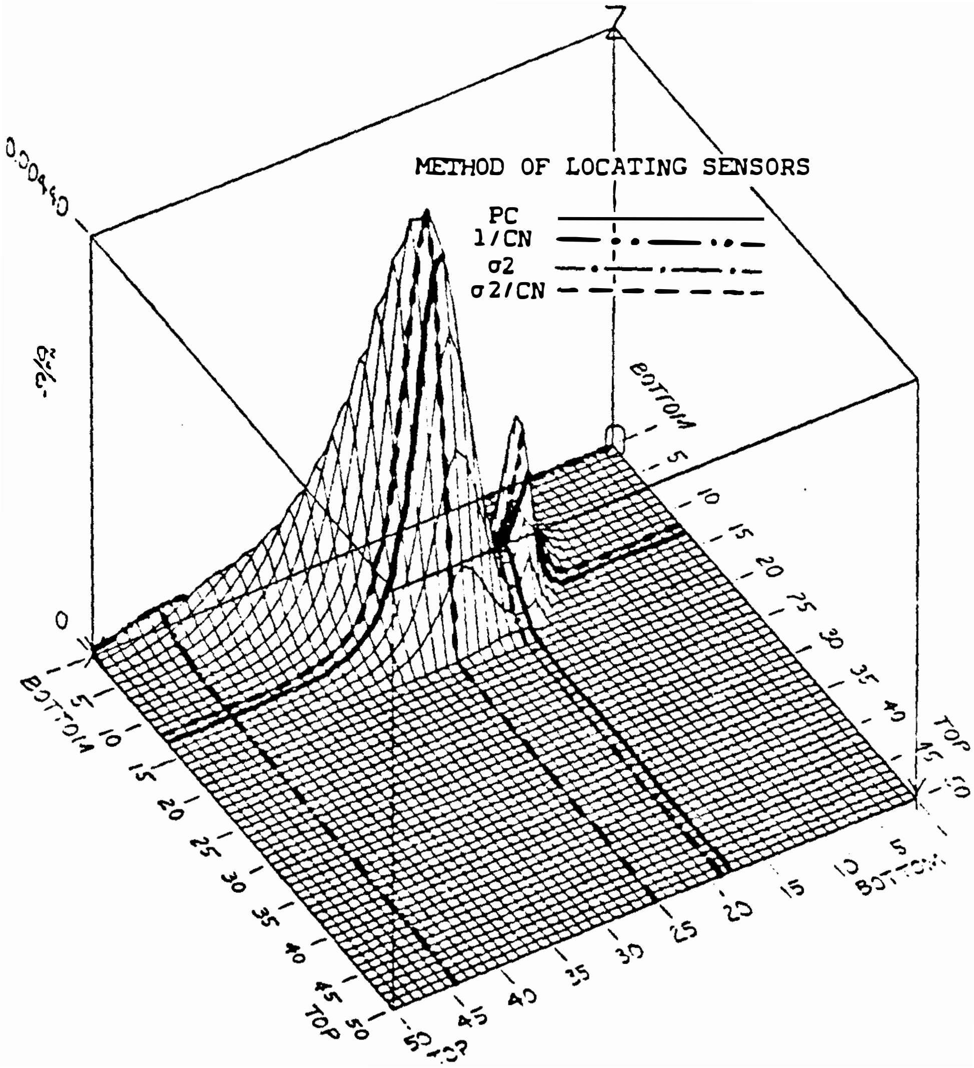

Figure 5.15: Intersivity Index Plot for DQ Scheme

methods have intersivities much lower than this peak. A more detailed summary of the top twenty trays from this method is located in Table 5.6. The main difference in this method over the principal component method is that the very sensitive tray 18 is avoided by shifting up to tray 25. Tray 18 is the most sensitive tray in the column as can be noted from the temperature profile in Figure 4.1.

The intersivity can be related to the λ values of Bristol's Relative Gain Array, since every 2×2 subsystem is investigated in the global search technique. Figure 5.16 illustrates that high intersivities correspond to good λ values. It is also interesting to note that λ's with a value close to unity do not necessarily correspond to high intersivities. The general trend in this plot is that the λ's approach unity as the intersivity increases. There is quite a bit of scatter at the lower intersivities but at values over approximately 0.002 the the plot is essentially a straight line.

5.4 Composition Studies

In recent years composition analyzers have been extensively developed. They have become less expensive and more reliable, thus making their use more reasonable. In anticipation of the increased use of such devices a SVD analysis was performed on composition gains.

When calculating composition gains one has several options that are not readily available for temperatures. The gains can be calculated for any

Table 5.6: Maximum Intersivity Index Search for DQ Method

First Sensor	Second Sensor	Condition Number	Singular Values		Intersivity
			σ_1	$\sigma_2 \times 10^2$	$\Xi \times 10^3$
25	12	9.68	0.412	4.26	4.40
26	11	8.36	0.298	3.56	4.25
25	11	9.51	0.380	4.00	4.21
24	12	11.6	0.547	4.71	4.06
24	13	12.1	0.576	4.78	3.97
26	10	8.27	0.268	3.24	3.91
26	12	9.31	0.337	3.62	3.89
25	13	10.8	0.450	4.17	3.87
27	10	7.51	0.215	2.86	3.81
27	11	8.40	0.252	2.99	3.56
24	11	12.2	0.524	4.28	3.49
25	10	10.3	0.358	3.49	3.40
27	9	7.50	0.190	2.53	3.38
23	13	15.5	0.803	5.16	3.32
28	9	6.91	0.156	2.25	3.26
24	14	13.7	0.605	4.41	3.21
23	12	15.7	0.782	4.97	3.16
28	10	7.69	0.186	2.41	3.14
26	13	11.2	0.382	3.42	3.06
26	9	9.08	0.248	2.73	3.01

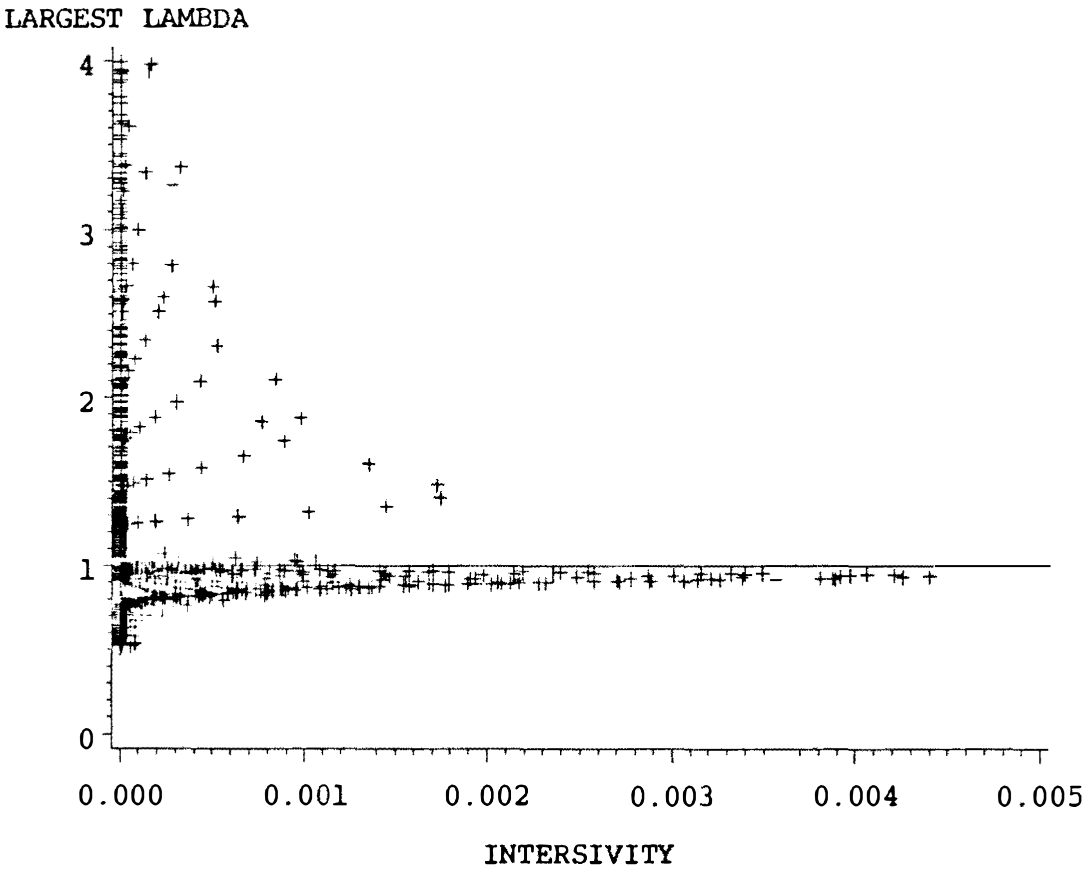

Figure 5.16: Intersivity Index vs. RGA λ

of the components in either the liquid or vapor phase. For the column in this study, that results in six combinations (3 components). To be certain that no possibility was overlooked, all six were investigated for each of the five convergence methods.

In every case the condition number of the system stayed about the same or improved for the vapor phase, while the liquid phase cases were significantly worsened, as compared to the temperature analysis. The condition numbers are organized in Table 5.7. The first singular values are also increased for both the liquid and the vapor phase, thus making the system more sensitive than the temperature analysis.

The SVD analyses in Table 5.7 were performed on composition gains that were scaled over the total span of composition from zero to one. It could be said that they were unscaled, depending on the viewpoint taken, since the scale factor is one. The compositions for different components should be scaled differently. It was decided that the most logical scaling would be to divide the delta sensor value by the base case value as is done on the valve values.

Analyzers are more flexible than ordinary temperature sensors, they can be "tuned" to a certain composition. Because of this flexibility the scale factors used were different for each component, each stage and each phase. There would only need to be two analyzers (or one that can be tuned to two different compositions) in the real process, but in this simulation there can be as many as needed.

The SVD analysis was performed on the composition gains that resulted

Table 5.7: SVD Analysis for Composition Gains

Method	Component	Phase	Condition No.	Singular Values	
BR	Ethanol	Vapor	75.5	2.81×10^{-1}	3.72×10^{-3}
BR	Ethanol	Liquid	236	3.19×10^{-1}	1.35×10^{-3}
BR	Water	Vapor	72.8	2.51×10^{-1}	3.45×10^{-3}
BR	Water	Liquid	236	2.85×10^{-1}	1.20×10^{-3}
BR	Fusel Oils	Vapor	96.6	3.10×10^{-2}	3.21×10^{-4}
BR	Fusel Oils	Liquid	165	3.52×10^{-2}	2.13×10^{-4}
QR	Ethanol	Vapor	138	4.16×10^{-1}	3.00×10^{-3}
QR	Ethanol	Liquid	435	4.73×10^{-1}	1.09×10^{-3}
QR	Water	Vapor	133	3.71×10^{-1}	2.78×10^{-3}
QR	Water	Liquid	435	4.22×10^{-1}	9.70×10^{-4}
QR	Fusel Oils	Vapor	176	4.57×10^{-2}	2.60×10^{-4}
QR	Fusel Oils	Liquid	301	5.20×10^{-2}	1.73×10^{-4}
DQ	Ethanol	Vapor	55.8	2.84×10^{-1}	5.09×10^{-3}
DQ	Ethanol	Liquid	3.55×10^{5}	2,110	5.93×10^{-3}
DQ	Water	Vapor	54.0	2.54×10^{-1}	4.71×10^{-3}
DQ	Water	Liquid	3.65×10^{5}	2,110	5.77×10^{-3}
DQ	Fusel Oils	Vapor	70.2	3.11×10^{-2}	4.43×10^{-4}
DQ	Fusel Oils	Liquid	5.49×10^{4}	18.4	3.36×10^{-4}
LB	Ethanol	Vapor	77.0	2.84×10^{-1}	3.68×10^{-3}
LB	Ethanol	Liquid	245	3.24×10^{-1}	1.33×10^{-3}
LB	Water	Vapor	74.5	2.54×10^{-1}	3.40×10^{-3}
LB	Water	Liquid	245	2.90×10^{-1}	1.18×10^{-3}
LB	Fusel Oils	Vapor	97.2	3.11×10^{-2}	3.20×10^{-4}
LB	Fusel Oils	Liquid	167	3.54×10^{-2}	2.13×10^{-4}
LQ	Ethanol	Vapor	1,030	3.07	2.98×10^{-3}
LQ	Ethanol	Liquid	3,290	3.51	1.07×10^{-3}
LQ	Water	Vapor	996	2.75	2.76×10^{-3}
LQ	Water	Liquid	3,290	3.14	9.53×10^{-4}
LQ	Fusel Oils	Vapor	1,300	3.36×10^{-1}	2.58×10^{-4}
LQ	Fusel Oils	Liquid	2,240	3.83×10^{-1}	1.71×10^{-4}

from the scaling method described earlier. The condition numbers for the scaled case are shown in Table 5.8. These results differ markedly from those of the unscaled case. For the ethanol cases the condition number improved by about an order of magnitude or more. The water cases stayed approximately the same, while the fusel oil values increased significantly.

A partial SVD analysis was performed on the systems indicated by the principal component method for the composition sensors and summarized in Table 5.9. Some of these sensors have very low 2×2 κ's the best being the DQ scheme measuring ethanol vapor with a κ of 5.78 and a λ of 1.010. It is interesting to note that there are some sensors that have good λ values but bad κ's. For example the DQ scheme measuring fusel oil liquid has a κ of 7.55×10^9 but a λ of 1.000.

It should be noted that in this study the sensors were of the same type (phase and component) for each individual study. It might be possible that a better control pairing could be achieved with "mixed sensors." For example, one could use the vapor composition of ethanol on tray 18 for one sensor and the liquid composition of water on tray 14 for the other. Temperature sensors could also be used in this concept. It is possible that one of the less favorable schemes in the current study could become more favorable with mixed sensors. With five control schemes, fifty trays and seven different sensor types (temperature and the six different compositions) one can see the enormity of the problem. This avenue was not studied here but should be investigated.

Table 5.8: SVD Analysis for Scaled Composition Gains

Method	Component	Phase	Condition No.	Singular Values	
BR	Ethanol	Vapor	10.5	1.21	1.16×10^{-1}
BR	Ethanol	Liquid	12.1	1.86	1.54×10^{-1}
BR	Water	Vapor	82.8	4.74×10^{-1}	5.73×10^{-3}
BR	Water	Liquid	98.7	4.94×10^{-1}	5.01×10^{-3}
BR	Fusel Oils	Vapor	181	7.41	4.09×10^{-2}
BR	Fusel Oils	Liquid	186	7.28	3.91×10^{-2}
QR	Ethanol	Vapor	17.8	1.77	9.99×10^{-2}
QR	Ethanol	Liquid	21.7	2.80	1.29×10^{-1}
QR	Water	Vapor	154	7.27×10^{-1}	4.71×10^{-3}
QR	Water	Liquid	185	7.60×10^{-1}	4.11×10^{-3}
QR	Fusel Oils	Vapor	335	11.3	3.38×10^{-2}
QR	Fusel Oils	Liquid	345	11.1	3.22×10^{-2}
DQ	Ethanol	Vapor	5.62	1.07	1.91×10^{-1}
DQ	Ethanol	Liquid	1.47×10^{4}	3,440	2.33×10^{-1}
DQ	Water	Vapor	57.6	4.78×10^{-1}	8.30×10^{-3}
DQ	Water	Liquid	1.73×10^{6}	1.15×10^{4}	6.65×10^{-3}
DQ	Fusel Oils	Vapor	124	7.40	5.98×10^{-2}
DQ	Fusel Oils	Liquid	2.70×10^{9}	1.52×10^{8}	5.65×10^{-2}
LB	Ethanol	Vapor	8.39	1.09	1.29×10^{-1}
LB	Ethanol	Liquid	11.1	1.79	1.61×10^{-1}
LB	Water	Vapor	84.1	4.78×10^{-1}	5.69×10^{-3}
LB	Water	Liquid	102	5.02×10^{-1}	4.94×10^{-3}
LB	Fusel Oils	Vapor	181	7.42	4.09×10^{-2}
LB	Fusel Oils	Liquid	187	7.31	3.91×10^{-2}
LQ	Ethanol	Vapor	111	12.0	1.08×10^{-1}
LQ	Ethanol	Liquid	1,51	20.0	1.33×10^{-1}
LQ	Water	Vapor	1,150	5.36	4.68×10^{-3}
LQ	Water	Liquid	1,380	5.62	4.07×10^{-3}
LQ	Fusel Oils	Vapor	2,470	83.0	3.37×10^{-2}
LQ	Fusel Oils	Liquid	2,540	81.7	3.21×10^{-2}

Table 5.9: Partial SVD Analysis for Scaled Composition Gains

Method	Component	Phase	Sensors	Condition No.	RGA(1,1)
BR	Ethanol	Vapor	18 - 1	25.9	1.014
BR	Ethanol	Liquid	18 - 1	15.5	0.985
BR	Water	Vapor	20 - 14	137	0.966
BR	Water	Liquid	38 - 21	149	1.190
BR	Fusel Oils	Vapor	28 - 15	99.1	1.010
BR	Fusel Oils	Liquid	28 - 17	110	1.000
QR	Ethanol	Vapor	18 - 1	17.1	-2.670
QR	Ethanol	Liquid	18 - 1	28.4	-2.610
QR	Water	Vapor	20 - 14	255	-7.620
QR	Water	Liquid	39 - 22	274	21.3
QR	Fusel Oils	Vapor	29 - 15	184	-2.820
QR	Fusel Oils	Liquid	28 - 15	214	-1.600
DQ	Ethanol	Vapor	18 - 1	5.78	1.010
DQ	Ethanol	Liquid	7 - 1	4,870	1.000
DQ	Water	Vapor	20 - 14	94.5	0.970
DQ	Water	Liquid	50 - 21	1.44×10^{6}	1.060
DQ	Fusel Oils	Vapor	28 - 15	67.5	1.000
DQ	Fusel Oils	Liquid	50 - 15	7.55×10^{9}	1.000
LB	Ethanol	Vapor	18 - 1	8.57	1.000
LB	Ethanol	Liquid	18 - 1	15.1	0.989
LB	Water	Vapor	31 - 19	174	1.110
LB	Water	Liquid	28 - 20	211	1.610
LB	Fusel Oils	Vapor	33 - 15	99.8	1.000
LB	Fusel Oils	Liquid	30 - 17	111	1.000
LQ	Ethanol	Vapor	18 - 1	116	20.5
LQ	Ethanol	Liquid	18 - 1	205	20.2
LQ	Water	Vapor	20 - 14	1,880	57.2
LQ	Water	Liquid	38 - 21	2,090	-162
LQ	Fusel Oils	Vapor	28 - 15	1,340	21.7
LQ	Fusel Oils	Liquid	28 - 15	1,570	12.7

5.5 Parametric Studies

The singular value analysis is a linear, steady state tool, thus it is possible that a slight modification in the operating conditions could give drastically different results because of the nonlinearity of the system. The nonlinearities necessitate the checking the SVD analysis at several operating points around the base case operating conditions.

Several of the basic operating variables were perturbed to give new steady states. The SVD analysis was then performed on the resulting gain matrix. The aspect of the SVD investigated at the new steady state is the condition number, which gives insight on the controllability of the process at the particular steady state. Changes of approximately ±5% and ±10% from the base case were made to see if there was a significant change in the κ of the SVD analysis. In this study the effect of a whole class of perturbations were studied in terms of their effect on the condition number. Only the results for the three most feasible control schemes (BR, DQ and LB) are presented here so that the details will be readily seen and not washed out by the large scale that would be necessary for the remaining two methods (QR and LQ).

The first set of parameters to be studied are those that concern disturbances that might be seen in an industrial column. The effect of a change in the distillate rate on the condition number is shown Figure 5.17. The curves have maximums at the base case flow rate of 21.0 $\mathrm{lb}_{\mathrm{mol}}$/hr. The condition number should have a maximum at this point since it is at the azeotrope of the system.

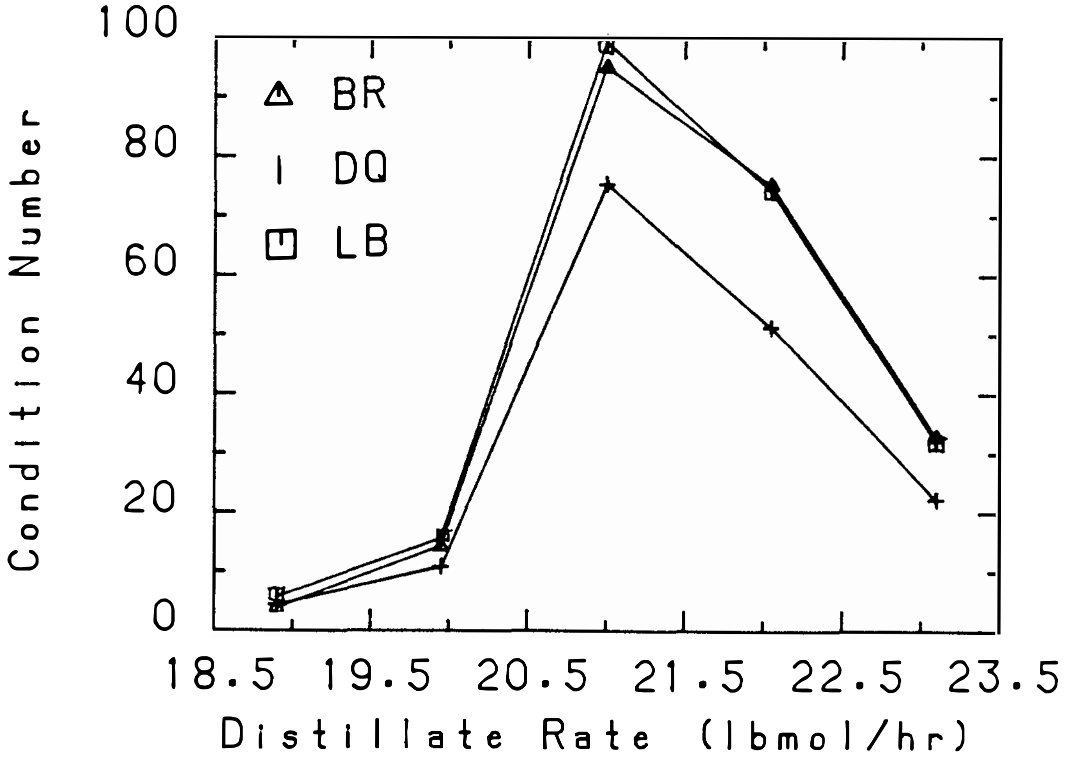

Figure 5.17: Parametric Study of Distillate Rate

The flow rates that were lower than the base case tended to have very small condition numbers. This is as should be expected since the smaller distillate rate means the column is operating at a much less constrained point with a smaller recovery of ethanol. Changes in the feed flow rate have similar results as shown in Figure 5.18. In this case however the least constrained direction is that of increased feed which also decreases the ethanol recovery. The condition number has a steady but small increase to changes in the reflux ratio. The curve in Figure 5.19 is almost linear. The feed temperature (Figure 5.20) and fusel oil feed composition (Figure 5.21) have virtually no effect on the condition number.

The last set of parameters to be investigated are those that are involved in the computer simulation. These parameters can be viewed as modeling errors. These are things that do not have handles in industrial column such as the physical parameters and the VLE of the components. The constant A for ethanol in the Antoine equation is varied in Figure 5.22. The condition number is very sensitive to changes in this parameter. A small change on either side of the "correct" value of 18.9119 would indicate that the control scheme was very well-conditioned with a small κ where the correct scheme is not so well-conditioned. The A value for water exhibits a similar trend (see Figure 5.23). The fusel oils A value has a much smaller effect as shown in Figure 5.24.

The same analysis was performed on the interaction parameters in the Wilson equation (see Figures 5.25–5.30). Two of the six parameters have a rather large effect on the condition number, these two are W(ethanol,water)

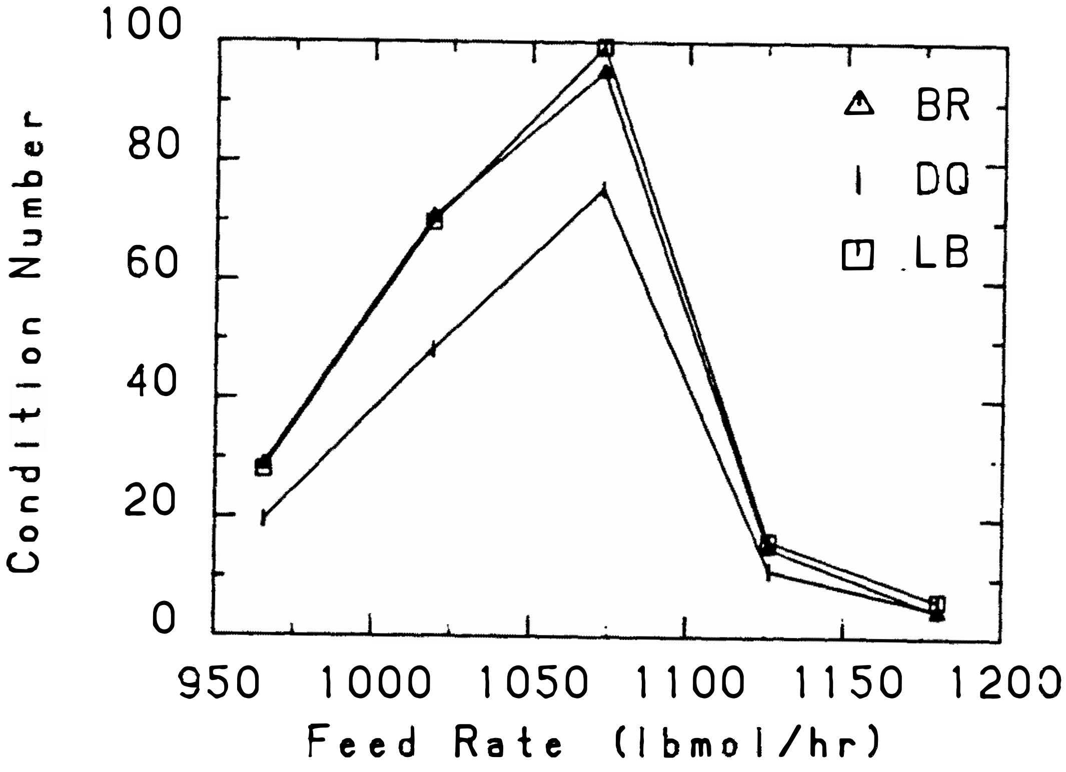

Figure 5.18: Parametric Study of Feed Rate

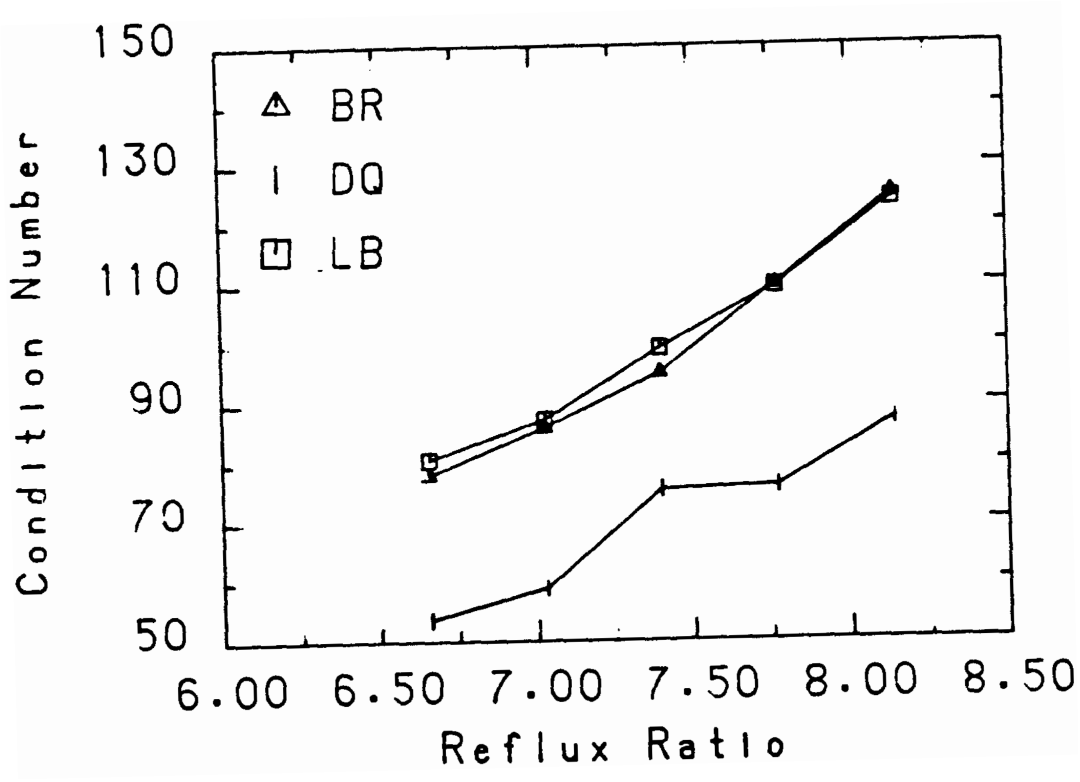

Figure 5.19: Parametric Study of Reflux Ratio

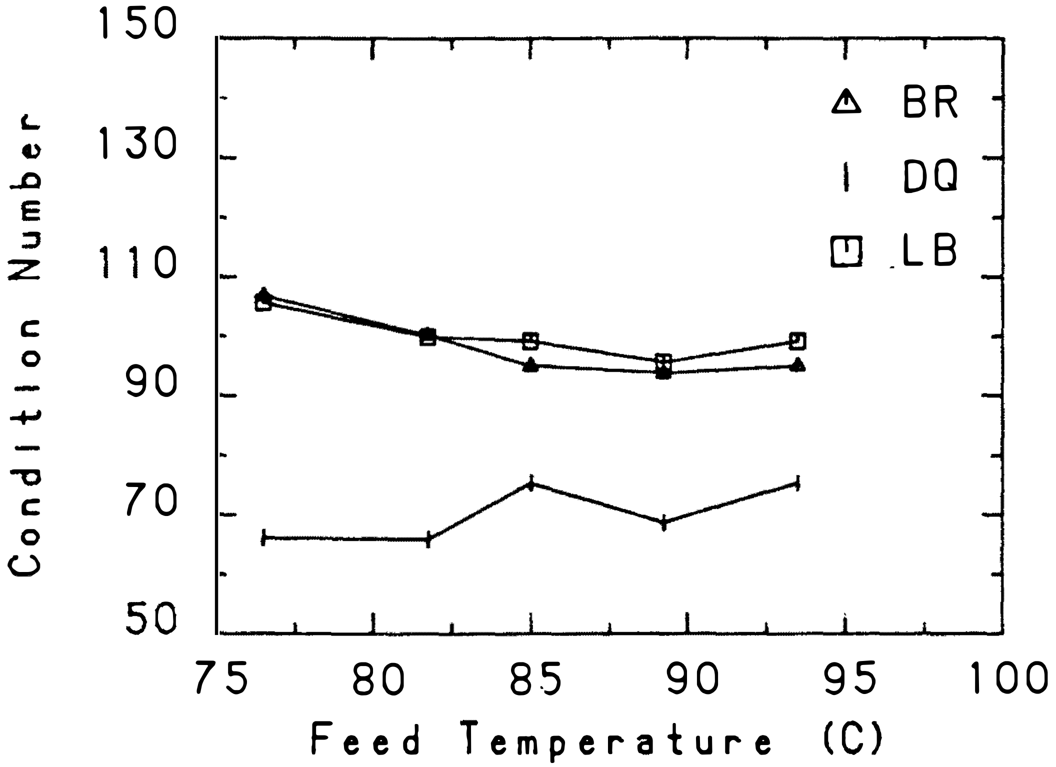

Figure 5.20: Parametric Study of Feed Temperature

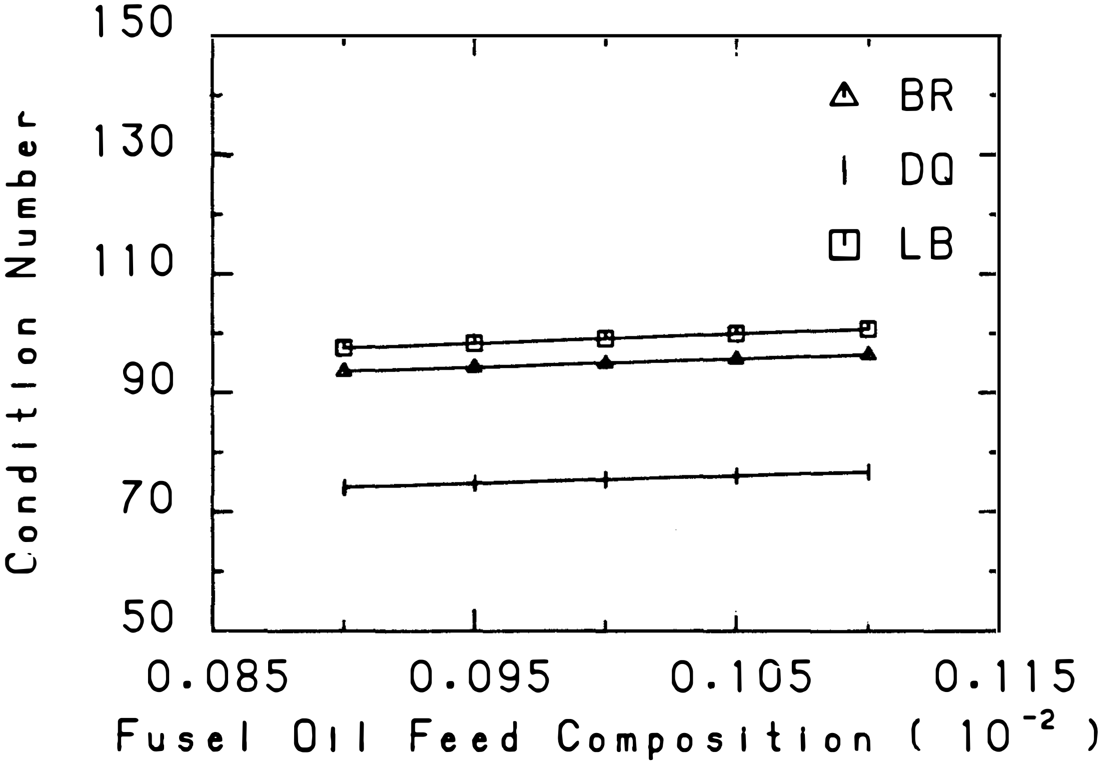

Figure 5.21: Parametric Study of Fusel Oil Feed Composition

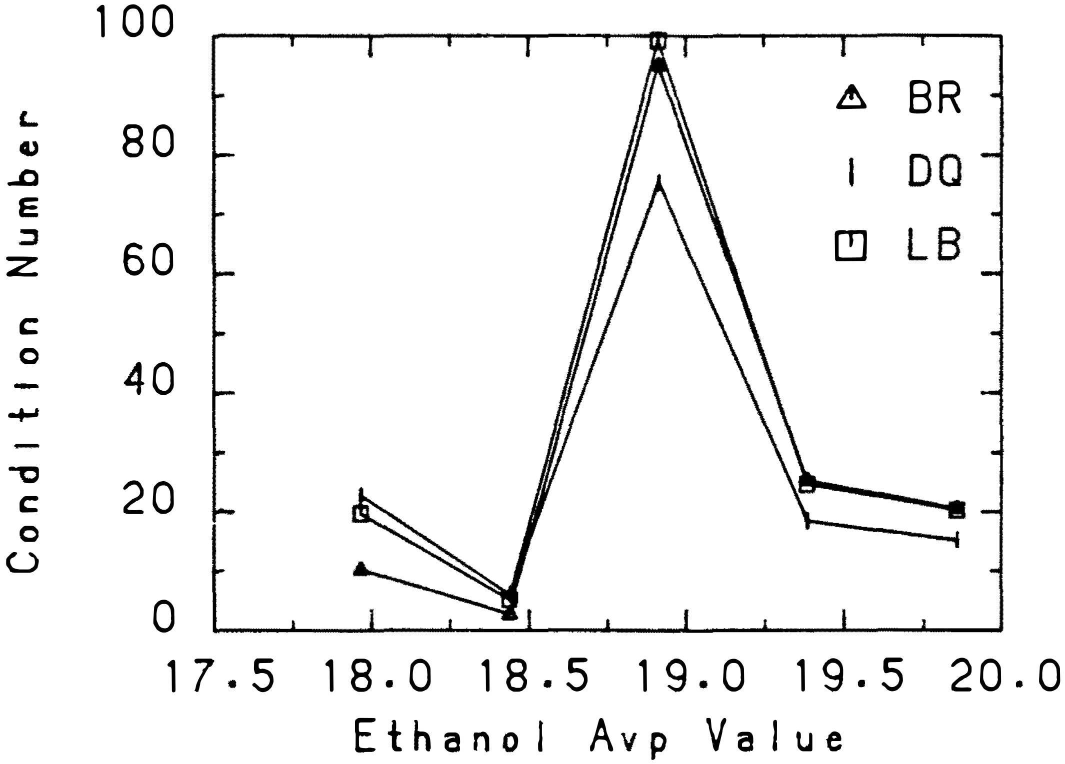

Figure 5.22: Parametric Study of Antoine A for Ethanol

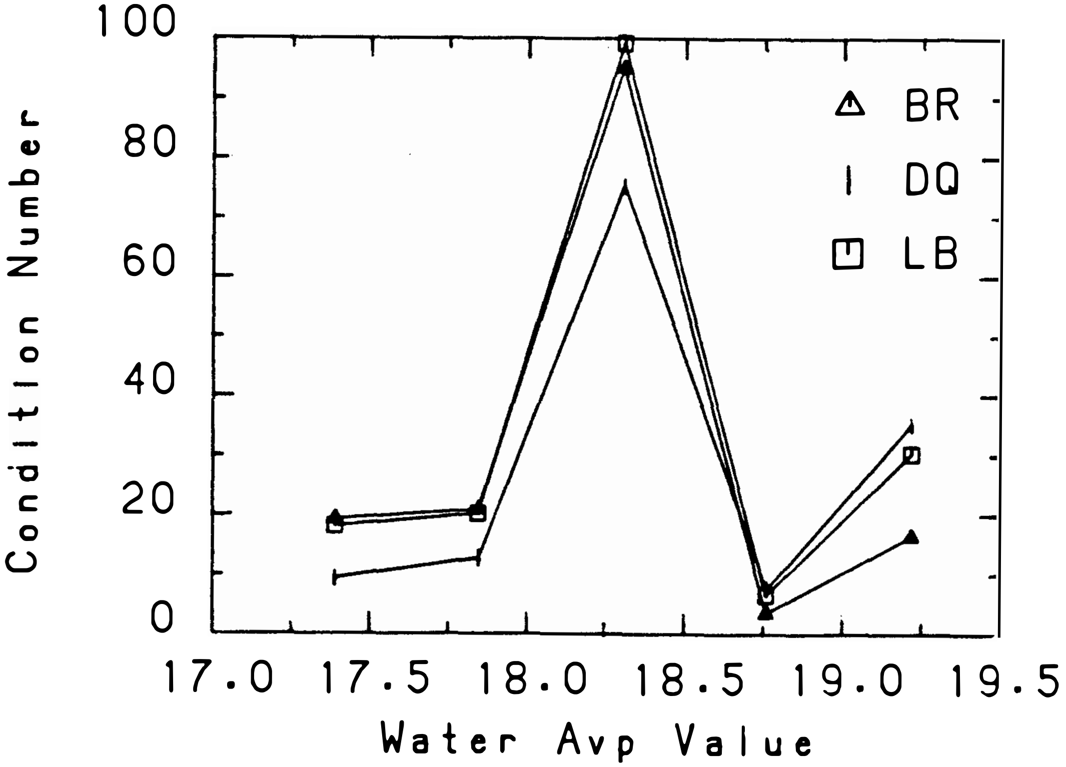

Figure 5.23: Parametric Study of Antoine A for Water

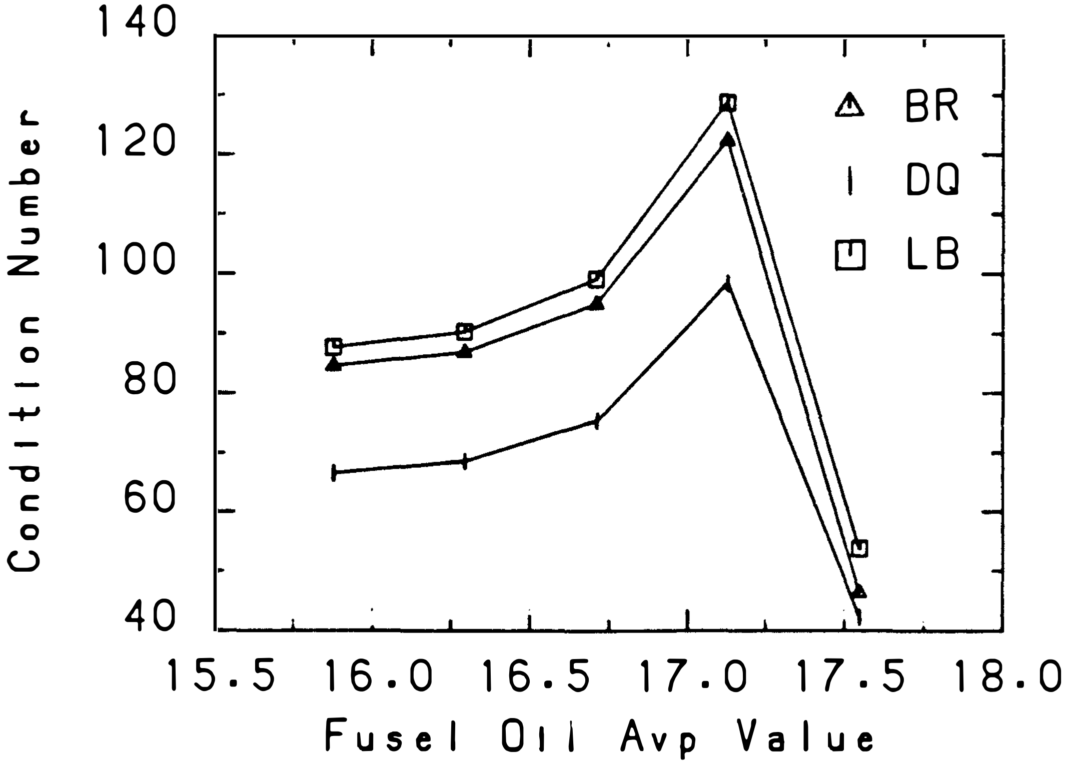

Figure 5.24: Parametric Study of Antoine A for Fusel oils

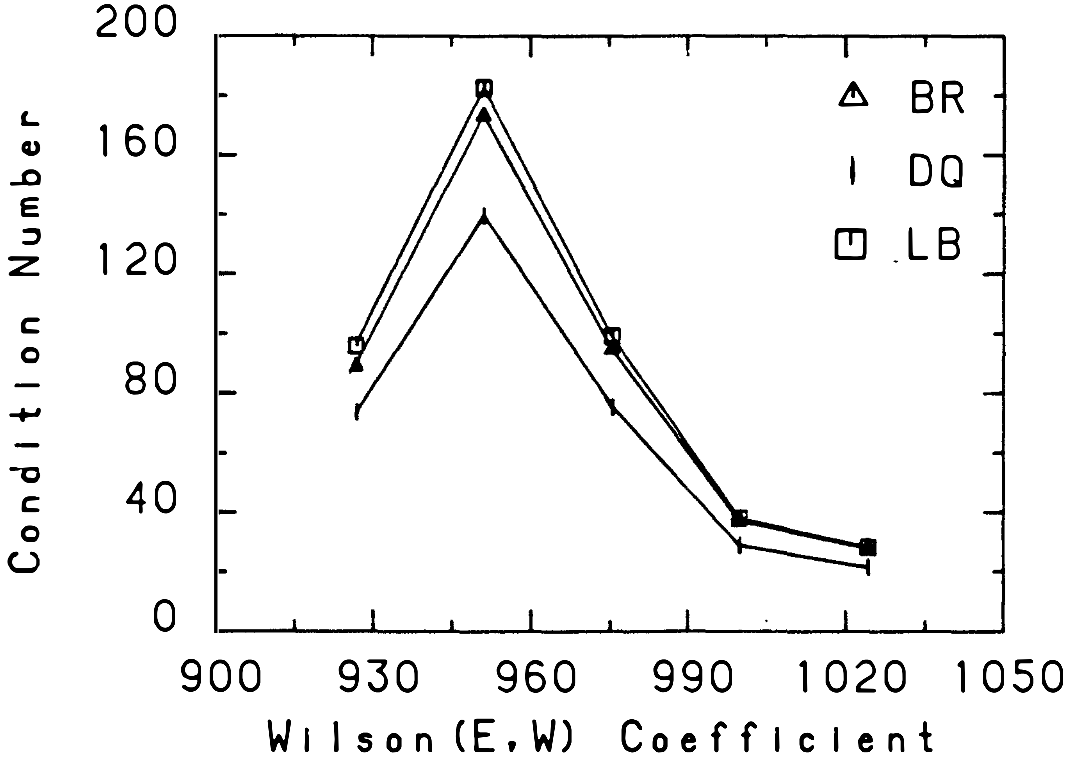

Figure 5.25: Parametric Study of Wilson Coefficient W(E,W)

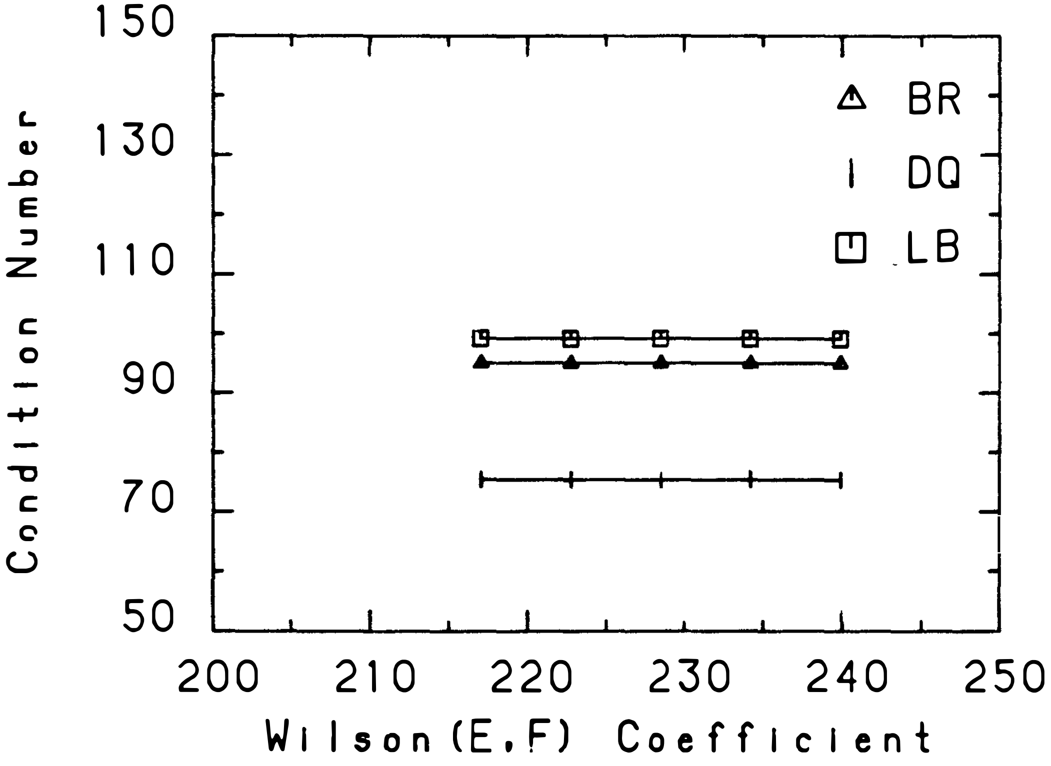

Figure 5.26: Parametric Study of Wilson Coefficient W(E,F)

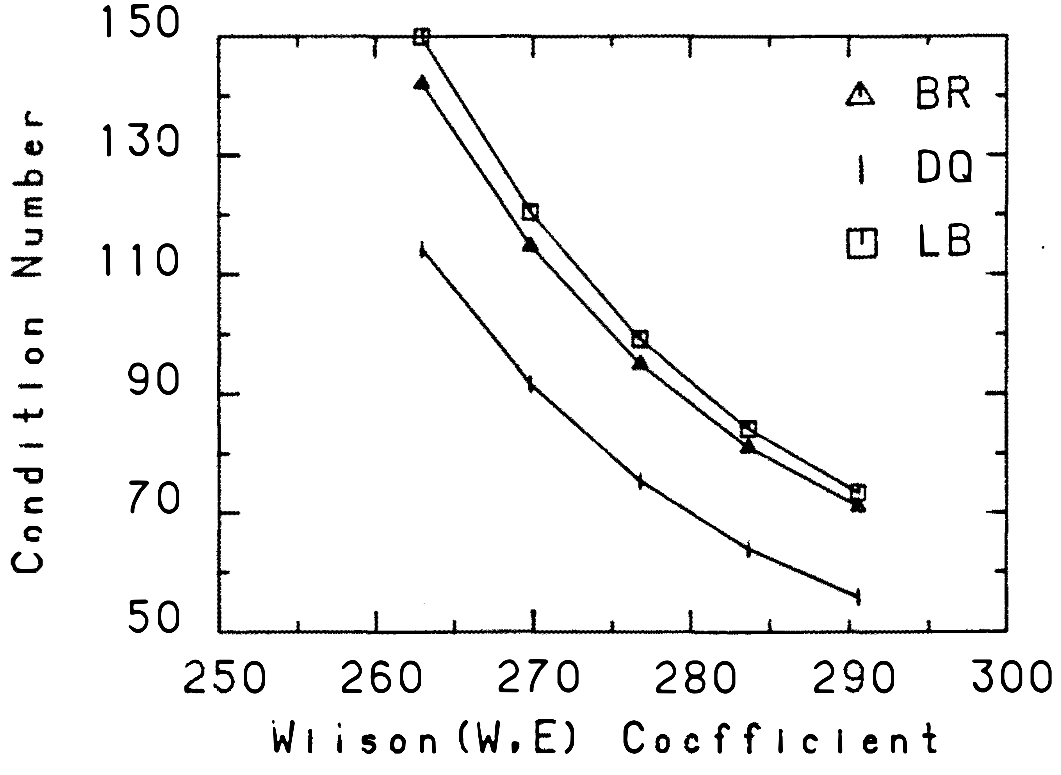

Figure 5.27: Parametric Study of Wilson Coefficient W(W,E)

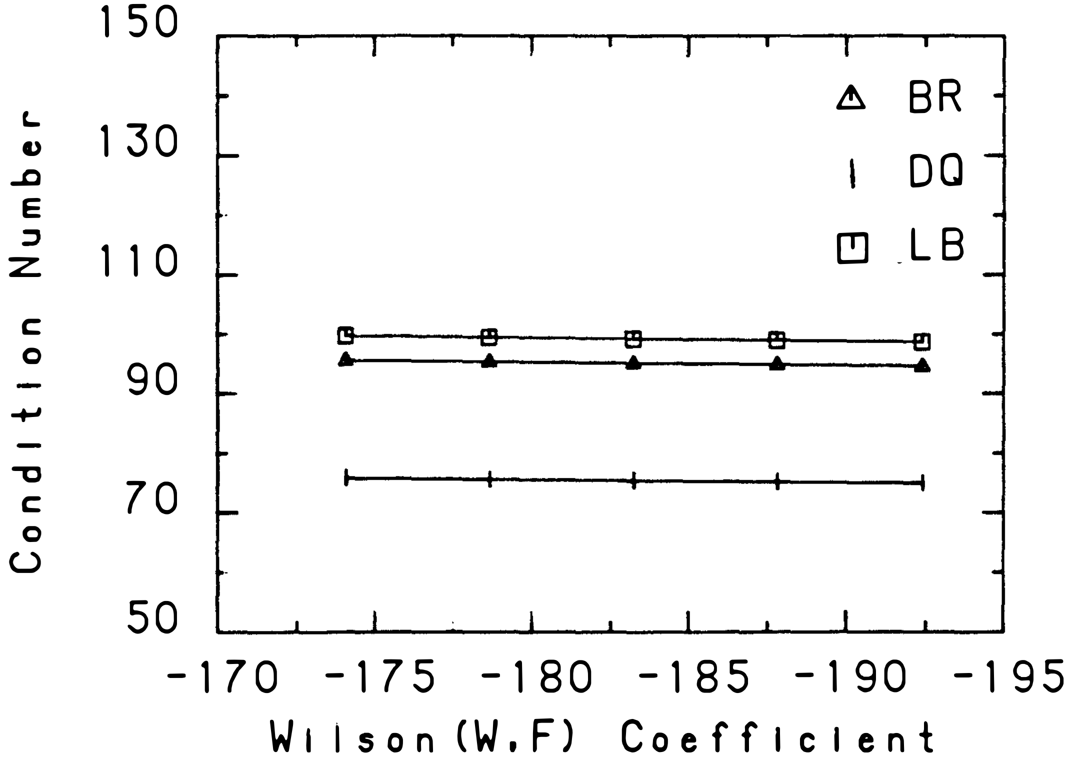

Figure 5.28: Parametric Study of Wilson Coefficient W(W,F)

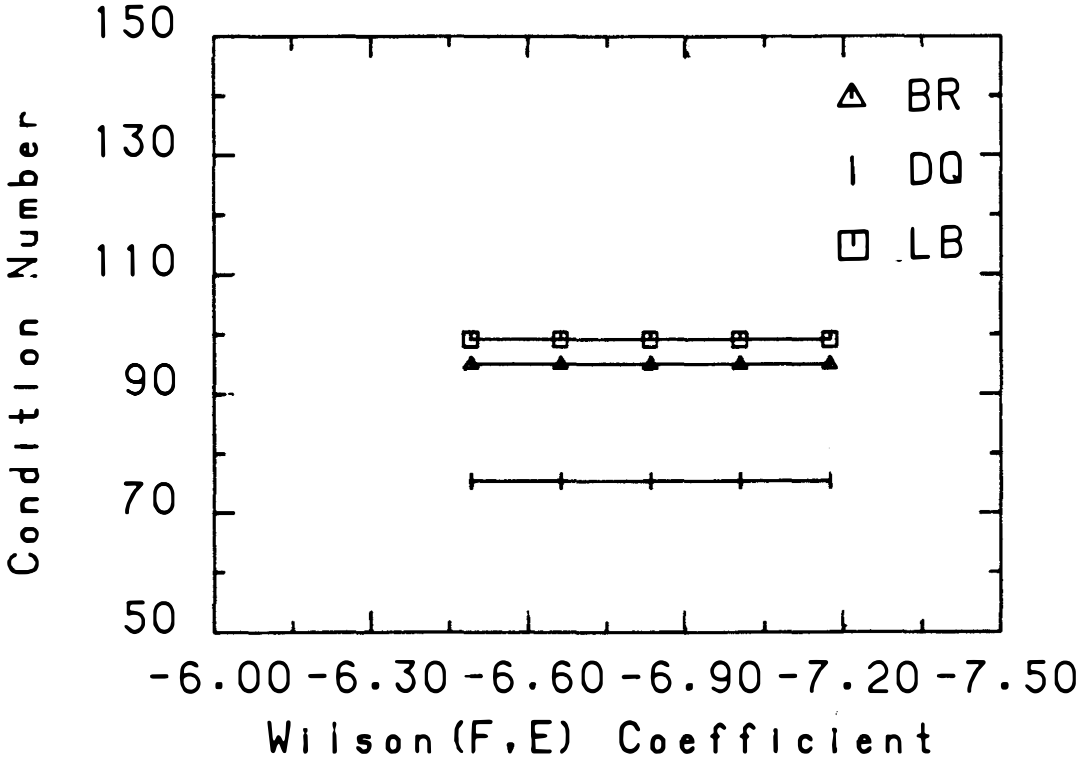

Figure 5.29: Parametric Study of Wilson Coefficient W(F,E)

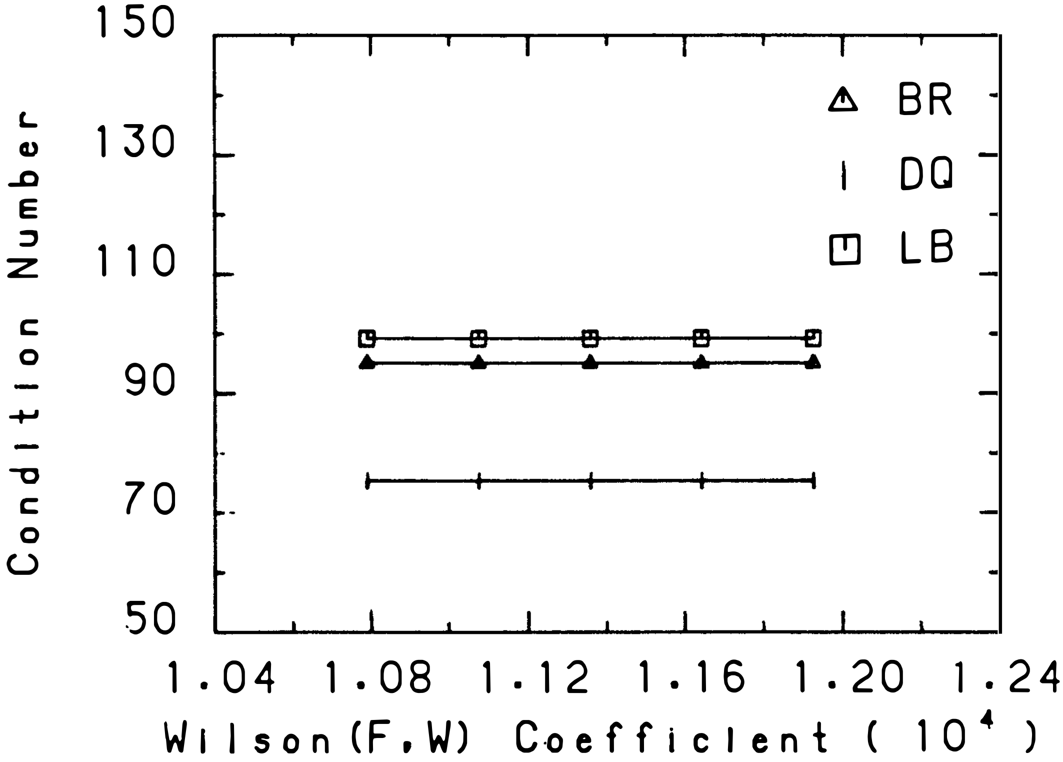

Figure 5.30: Parametric Study of Wilson Coefficient W(F,W)

and W(water,ethanol). The remaining four parameters that all involve the fusels have little if any effect on the condition number. Since the fusels have such a small concentration in the column it is understandable that their Wilson parameters would have little effect on the system.

The critical temperatures and pressures were also studied and found to have little or no effect on the κ for any of the three components (see Figures 5.31–5.36). There are several other parameters that could also be investigated, but the purpose of this study is merely to illustrate that the nonlinearities of the system can have severe effects on the SVD analysis.

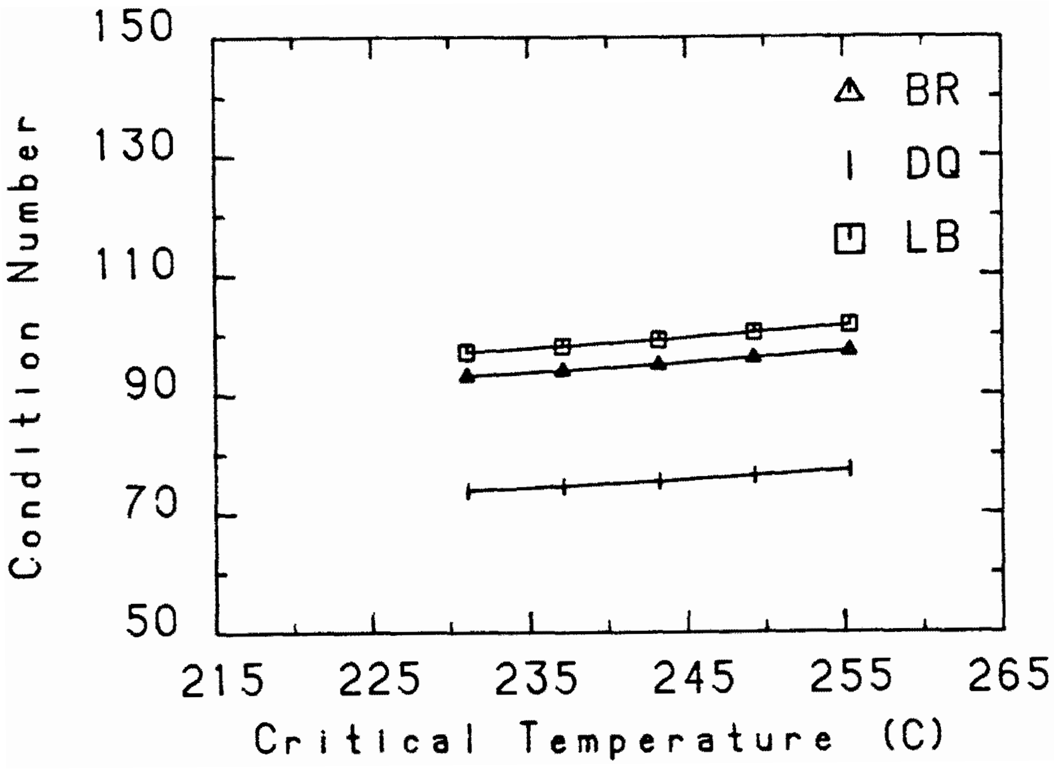

Figure 5.31: Parametric Study of Critical Temperature of Ethanol

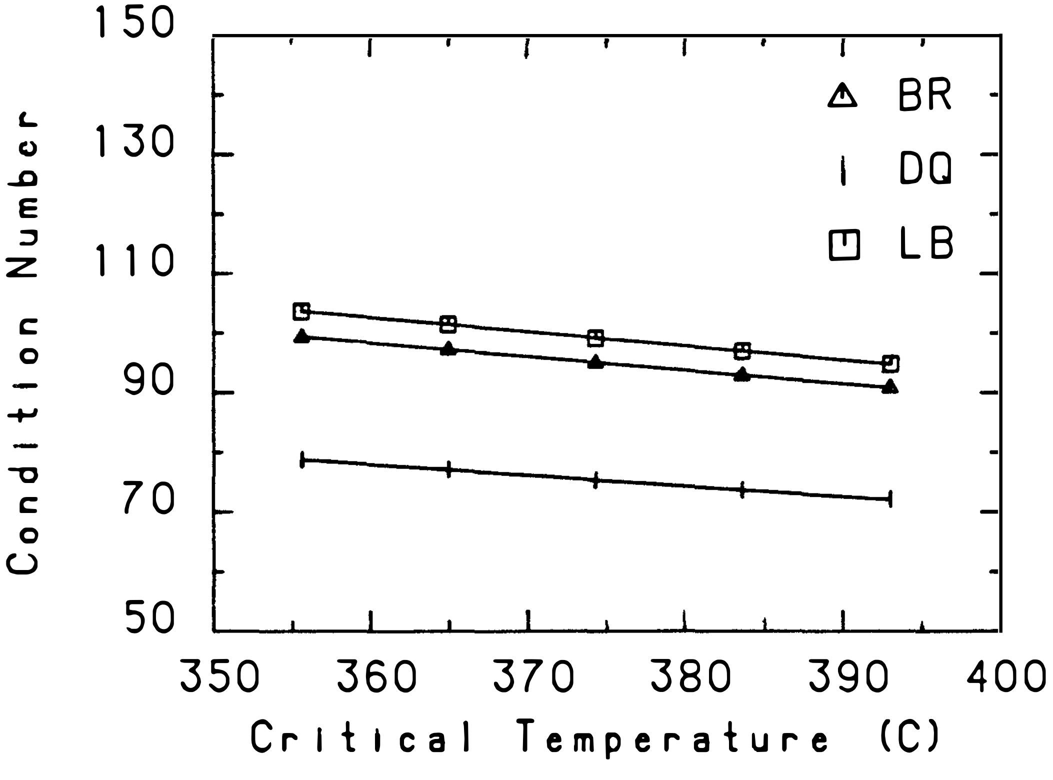

Figure 5.32: Parametric Study of Critical Temperature of Water

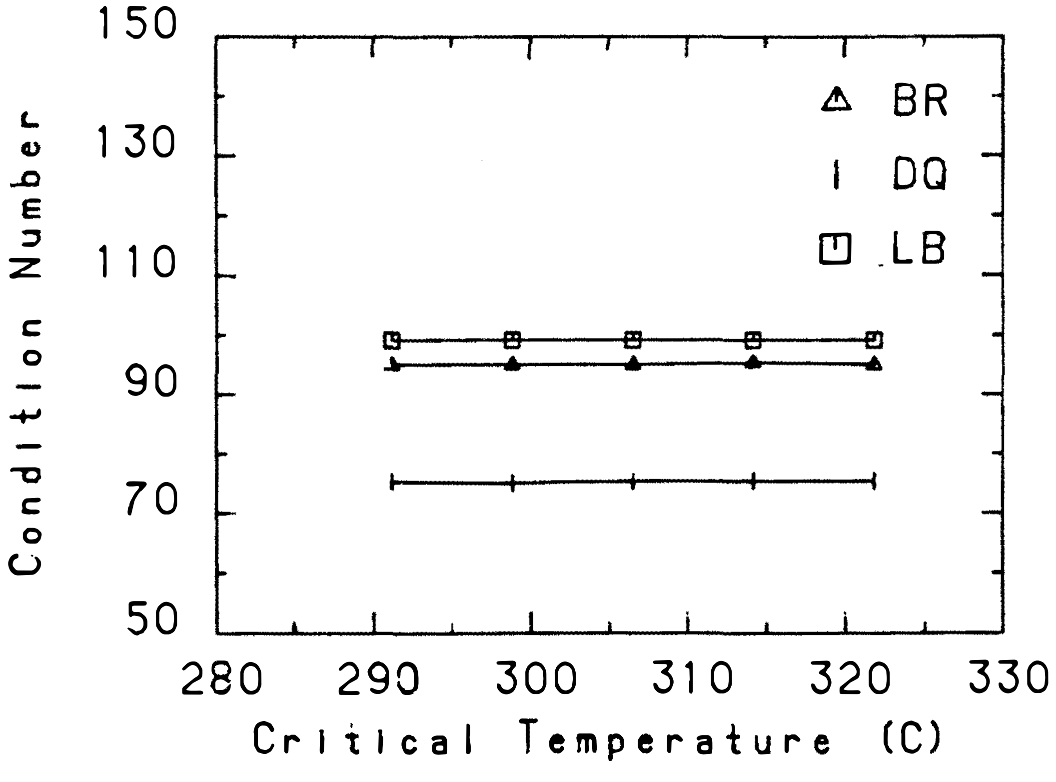

Figure 5.33: Parametric Study of Critical Temperature of Fusel Oils

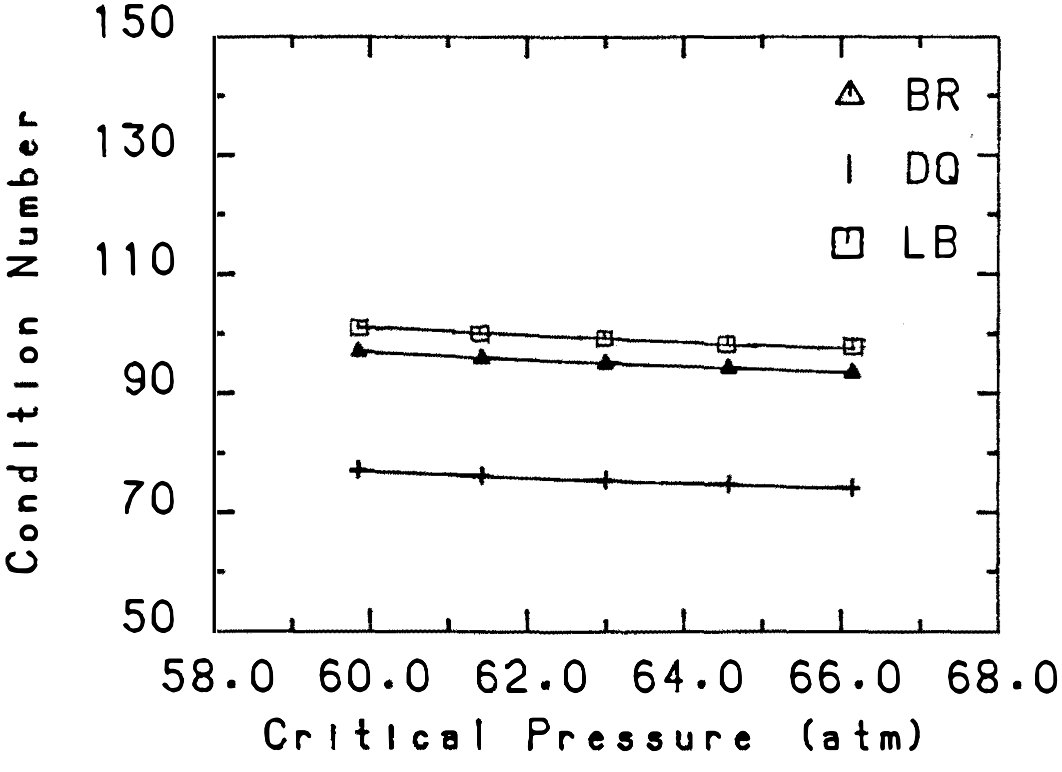

Figure 5.34: Parametric Study of Critical Pressure of Ethanol

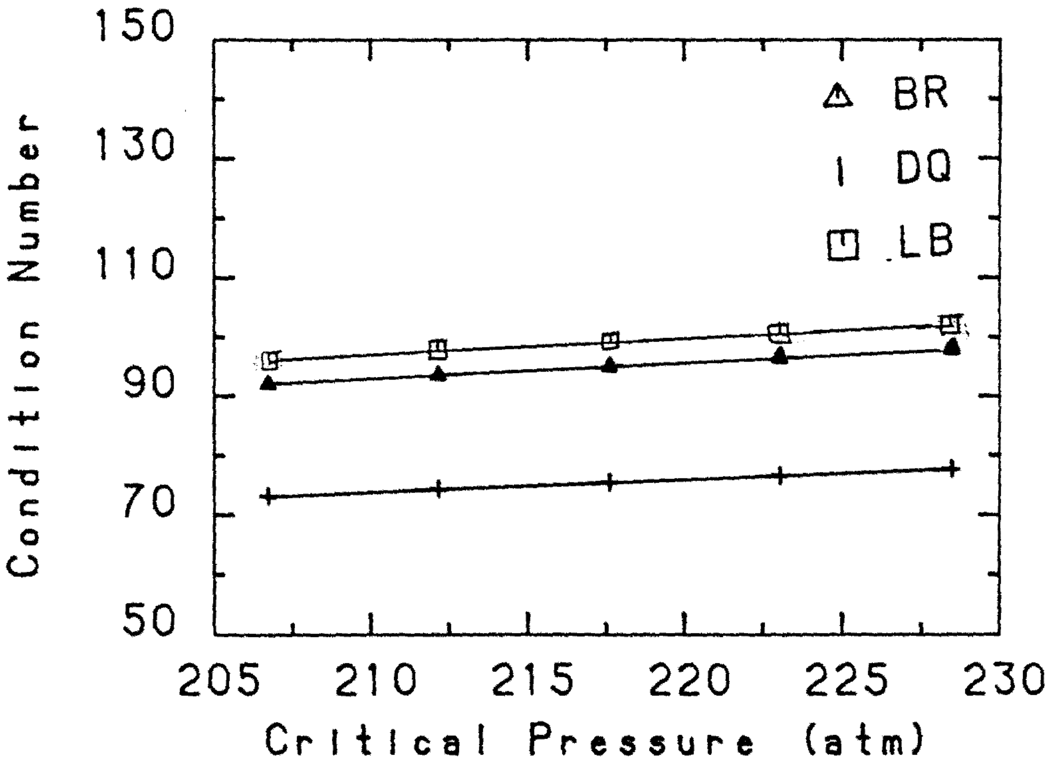

Figure 5.35: Parametric Study of Critical Pressure of Water

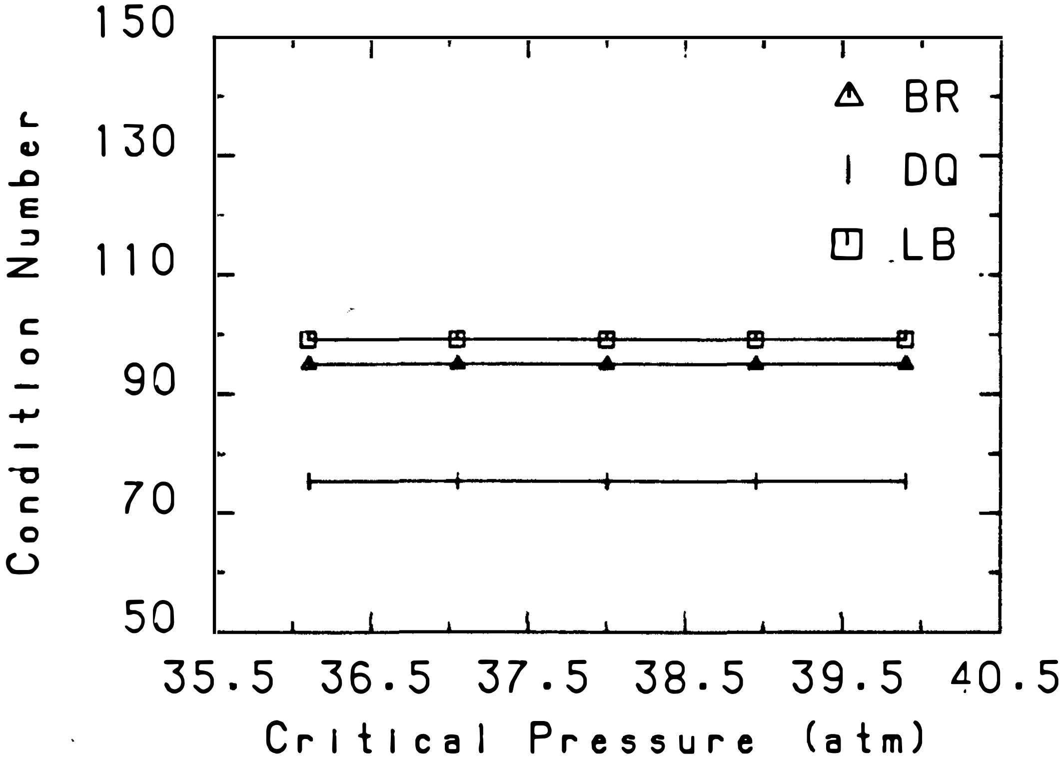

Figure 5.36: Parametric Study of Critical Pressure of Fusel Oils

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

From the work presented in this study the following conclusions can be drawn.

1. The sidedraw operation does not have a large impact on the overall column operation.
2. The steam usage plays a major role in the economic considerations of the column operation.
3. The DQ control scheme is the most promising for dual-ended control of the column.
4. The intersivity index seems to be a good method of locating sensors.
5. Interior composition sensors result in better conditioned control schemes than temperature sensors.
6. The SVD analysis changes as the operating conditions change.
7. Inaccurate physical property and VLE parameters can lead to inaccurate results in the SVD analysis

There seems to be a need for further research into the intersivity index. The results presented here should be checked further by a dynamic simulation and it should be extended to composition gains and should be tested on other columns. There is even more work that could be performed on this particular column because the DQ scheme was the only one that was investigated by the intersivity index. Since the composition sensors seem to give the most well-conditioned systems they should be investigated further. As mentioned in Chapter 5 there is the possibility of using "mixed sensors" that might give even more well-conditioned systems.

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APPENDIX

```
                    MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM          DATE/TIME :18-MAY-1987 16:28:52.60

          ETHANOL RECOVERY STILL
               BASE CASE SVO STUDY


                                        LISTING OF INPUT DATA

NCOMP NTRAY NOFEED NOSIDE IWILS IGAMMA IFE INITE INITQ IDUG ICUTOP KMAX JMAXT JMAXV BMETH TMETH IOPT KIMAX ICTYPE
----- ----- ------ ------ ----- ------ --- ----- ----- ---- ------ ---- ----- ----- ----- ----- ---- ----- ------
  3    50     1      1      0     1     1    0     1     0     1     99   99    99     1     3     1    0     1

   EPS1       EPS2       EPS3       ATEMP      AVAP
   ----       ----       ----       -----      ----
 0.10E-13   0.10E-04   0.10E-02   0.50E-01   0.50E-01

 DISTILLATE     REFLUX     PTOP      PBOT      TTOP      TBOT      TREF     EFF
 MOLES/HR       RATIO      TORR      TORR      DEG C     DEG C     DEG C
 ----------     ------     ----      ----      -----     -----     -----    ---
 0.21000E+02     7.400     760.00    915.00     78.30    103.80     68.00   0.50

FEED DATA
                                                                                MOLE FRACTION(Z(I,NN))
       N(J)              F(NN)         TF(J)   PF(J)
  J    (NN)    JTYPE   MOLES/HR        DEG C   TORR       1       2       3       4       5       6       7       8       9      10
 ---   ----    -----   -----           -----   -----    -----   -----   -----   -----   -----   -----   -----   -----   -----   -----
  1     16      L      0.10726E+04     85.00    840.00 0.01700 0.98200 0.00100

 LIQUID SIDE DRAW LOCATED ON TRAY 18

           COMPONENT DATA

  NAME      XMW       AVP          BVP        CVP        AH        BH          CH          DH         AV         BV          CV          DV         VOL
  ----     -----     -----        -----      -----      -----     -----       -----       -----      -----      -----       -----       -----      -----
ETHANOL    46.00   18.910000    -3804.00    231.40    0.4986   2.90E-03   0.00E+00   0.00E+00    396.20  -1.82E-01  -4.00E-03   0.00E+00    58.69
WATER      18.01   18.300000    -3816.00    226.90    1.0000  -2.00E-04   0.00E+00   0.00E+00   1073.00  -1.02E+00   7.00E-04   0.00E+00    18.07
FUSELS     88.15   16.710000    -3026.00    168.90    0.5239  -1.00E-03   1.00E-04   0.00E+00    215.80   0.00E+00   0.00E+00   0.00E+00   109.20

                   DENSITY PARAMETERS                                  VISCOSITY PARAMETERS              SURFACE TENSION PARAMETERS

  NAME          AD              BO             CD               AMU           BMU            CMU           ASURFT         BSURFT
  ----          --              --             --               ---           ---            ---           ------         ------
ETHANOL   0.494000E+02   -.343000E-01   -.173000E-03     0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
WATER     0.629300E+02   -.171600E-01   0.142700E-03     0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00
FUSELS    0.505400E+02   0.000000E+00   0.000000E+00     0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00   0.00000E+00

          BINARY DATA FOR WILSON EQ,DLAM(I,J)

   J            1           2           3
   1   DLAM 0.00000E+00 0.97550E+03 0.22850E+03
   2   DLAM 0.27680E+03 0.00000E+00-0.18320E+03
   3   DLAM-0.68320E+01 0.11360E+05 0.00000E+00

          DATA FOR VAPOR FUGACITY COEFFICIENTS REDLICH-KWONG EQN

                 1            2            3            4            5            6            7            8            9           10
CRIT TEMP(C) 243.20        374.30       306.50
CRIT P(ATM)   63.00        217.60        38.00

   BOTTOM SPECIFICATION: REBOILER DUTY =      0.37011E+07

    TOP SPECIFICATION: DISTILLATE RATE =   21.00000
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                          MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM          DATE :18-MAY-1987  TIME :16:28:52.60
ETHANOL RECOVERY STILL
       BASE CASE SVD STUDY
    +

                                          RESULTS OF THE DISTILLATION PROGRAM

     REFLUX RATIO      =  7.402                                 REBOILER DUTY     = 3.70110E+06  Btu/hr
     CONDENSER DUTY    = 3.03812E+06  Btu/hr                    NUMBER OF STAGES = 50

--------------------------------------------------------------------------------------------------------------------------------------
 OVERHEAD
+-----------------------+-----------------------+----------------------------+--------------------+
|      Temperature      |       Pressure        |         Enthalpy           | Avg.Mol.Weight     |
+-----------------------+-----------------------+----------------------------+--------------------+
|       68.00  Deg. C   |    760.00      Torr   |  3198.04        Btu/mole   |    42.0764         |
|      154.40  Deg. F   |     14.70      Psia   |  76.0055         Btu/lb    |                    |
+-----------------------+-----------------------+----------------------------+--------------------+
                   RATES
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
|    Component Name     |   Mole Fraction   |  Weight Fraction  |     Moles/hr      |      Lbs/hr       | Percent Recovery  |
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
|      ETHANOL          |   0.859821        |  0.939999         |     18.0563       |     830.588       |   0.9902          |
|      WATER            |   0.140178        |  6.000073E-02     |     2.94375       |     53.0169       |   2.7947E-03      |
|      FUSELS           |   2.537424E-09    |  5.315900E-09     |   5.328591E-08    |   4.697153E-06    |   4.9678E-08      |
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
|        Total          |     1.000000      |     1.000000      |     21.0000       |     883.604       |       ---         |
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+

--------------------------------------------------------------------------------------------------------------------------------------
 BOTTOMS
+-----------------------+-----------------------+----------------------------+--------------------+
|      Temperature      |       Pressure        |         Enthalpy           | Avg.Mol.Weight     |
+-----------------------+-----------------------+----------------------------+--------------------+
|      105.33  Deg. C   |    915.00      Torr   |  3389.20        Btu/mole   |    18.0809         |
|      221.59  Deg. F   |     17.69      Psia   |  187.446         Btu/lb    |                    |
+-----------------------+-----------------------+----------------------------+--------------------+
                   RATES
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
|    Component Name     |   Mole Fraction   |  Weight Fraction  |     Moles/hr      |      Lbs/hr       | Percent Recovery  |
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
|      ETHANOL          |   5.576720E-05    |  1.418782E-04     |   5.850704E-02    |     2.69132       |   3.2086E-03      |
|      WATER            |   0.998955        |  0.995036         |     1048.03       |     18875.1       |   0.9950          |
|      FUSELS           |   9.890908E-04    |  4.822115E-03     |     1.03768       |     91.4719       |   0.9674          |
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+
|        Total          |     1.000000      |     1.000000      |     1049.13       |     18969.3       |       ---         |
+-----------------------+-------------------+-------------------+-------------------+-------------------+-------------------+

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                                RESULTS OF THE DISTILLATION PROGRAM

 LIQUID FEED LOCATED ON TRAY 16
+----------------------+---------------------+-------------------------+-----------------+
|     Temperature      |      Pressure       |      Enthalpy           | Avg.Mol.Weight  |
+----------------------+---------------------+-------------------------+-----------------+
|     85.00  Deg. C    |     840.00    Torr  |  2767.07       Btu/mole |   . 18.5560     |
|    185.00  Deg. F    |      16.24    Psia  |  149.120       Btu/lb   |                 |
+----------------------+---------------------+-------------------------+-----------------+
                 RATES
+----------------------+------------------+------------------+------------------+------------------+
|   Component Name     |  Mole Fraction   |  Weight Fraction |    Moles/hr      |      Lbs/hr      |
+----------------------+------------------+------------------+------------------+------------------+
|     ETHANOL          |  1.700000E-02    |  4.214277E-02    |    18.2347       |     838.797      |
|     WATER            |  0.982000        |  0.953107        |    1053.32       |     18970.3      |
|     FUSELS           |  1.000000E-03    |  4.750493E-03    |    1.07263       |     94.5523      |
+----------------------+------------------+------------------+------------------+------------------+
|      Total           |    1.000000      |    1.000000      |    1072.63       |     19903.7      |
+----------------------+------------------+------------------+------------------+------------------+

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 LIQUID SIDE DRAW LOCATED ON TRAY  18
+----------------------+---------------------+-------------------------+-----------------+
|     Temperature      |      Pressure       |      Enthalpy           | Avg.Mol.Weight  |
+----------------------+---------------------+-------------------------+-----------------+
|     94.92  Deg. C    |     861.22    Torr  |  3262.48       Btu/mole |    20.3334      |
|    202.85  Deg. F    |      16.65    Psia  |  160.449       Btu/lb   |                 |
+----------------------+---------------------+-------------------------+-----------------+
                 RATES
+----------------------+------------------+------------------+------------------+------------------+------------------+
|   Component Name     |  Mole Fraction   |  Weight Fraction |    Moles/hr      |      Lbs/hr      | Percent Recovery |
+----------------------+------------------+------------------+------------------+------------------+------------------+
|     ETHANOL          |  4.798059E-02    |  0.108546        |   0.119951       |     5.51777      |    6.5782E-03    |
|     WATER            |  0.938041        |  0.830856        |   2.34510        |     42.2353      |    2.2264E-03    |
|     FUSELS           |  1.397804E-02    |  6.059804E-02    |   3.494509E-02   |     3.08041      |    3.2579E-02    |
+----------------------+------------------+------------------+------------------+------------------+------------------+
|      Total           |    1.000000      |    1.000000      |    2.50000       |     50.8335      |       ---        |
+----------------------+------------------+------------------+------------------+------------------+------------------+
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                MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM            DATE :18-MAY-1987  TIME :16:28:52.60
ETHANOL RECOVERY STILL
     BASE CASE SVD STUDY
  +

      INITIAL STAGE PROFILES

+-----+---------+---------+-------------+--------------+--------------+-------------+-------------+--------------+--------+-----------+
|Stage|  Temp.  | Press.  |    Vapor    |    Liquid    |     Feed     | Liq. Side   | Vap. Side   |     Feed     | Stage  |Heat Added |
| No. |  Deg.C  |  Torr   |  Moles/hr   |   Moles/hr   |   Moles/hr   |  Moles/hr   |  Moles/hr   |    Btu/hr    |  Eff.  |  Btu/hr   |
+-----+---------+---------+-------------+--------------+--------------+-------------+-------------+--------------+--------+-----------+
|  50 |  78.13  |  760.0  |  176.43     |  160.58      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  49 |  78.24  |  763.2  |  181.58     |  160.59      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  48 |  78.35  |  766.3  |  181.59     |  160.59      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  47 |  78.45  |  769.5  |  181.59     |  160.59      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  46 |  78.56  |  772.7  |  181.59     |  160.58      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  45 |  78.66  |  775.8  |  181.58     |  160.58      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  44 |  78.77  |  779.0  |  181.58     |  160.57      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  43 |  78.88  |  782.1  |  181.57     |  160.56      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  42 |  78.98  |  785.3  |  181.56     |  160.54      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  41 |  79.09  |  788.5  |  181.54     |  160.52      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  40 |  79.20  |  791.6  |  181.52     |  160.49      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  39 |  79.31  |  794.8  |  181.49     |  160.46      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  38 |  79.42  |  798.0  |  181.46     |  160.43      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  37 |  79.53  |  801.1  |  181.43     |  160.38      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  36 |  79.64  |  804.3  |  181.38     |  160.33      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  35 |  79.76  |  807.4  |  181.33     |  160.27      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  34 |  79.87  |  810.6  |  181.27     |  160.19      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  33 |  79.99  |  813.8  |  181.19     |  160.11      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  32 |  80.12  |  816.9  |  181.11     |  160.00      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  31 |  80.25  |  820.1  |  181.00     |  159.87      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  30 |  80.40  |  823.3  |  180.87     |  159.72      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  29 |  80.55  |  826.4  |  180.72     |  159.54      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  28 |  80.73  |  829.6  |  180.54     |  159.31      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  27 |  80.93  |  832.8  |  180.31     |  159.03      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  26 |  81.17  |  835.9  |  180.03     |  158.67      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  25 |  81.48  |  839.1  |  179.67     |  158.21      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  24 |  81.88  |  842.2  |  179.21     |  157.62      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  23 |  82.43  |  845.4  |  178.62     |  156.83      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  22 |  83.24  |  848.6  |  177.83     |  155.77      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  21 |  84.48  |  851.7  |  176.77     |  154.36      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  20 |  86.51  |  854.9  |  175.36     |  152.57      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  19 |  90.01  |  858.1  |  173.57     |  150.99      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  18 |  94.92  |  861.2  |  171.99     |  148.31      |      --      |    2.500    |     --      |      --      | 0.500  |    --     |
|  17 |  98.58  |  864.4  |  171.81     |  148.85      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  16 |  99.70  |  867.6  |  172.35     |  1250.6      |    1072.6    |     --      |     --      |    2767.1    | 0.500  |    --     |
|  15 | 100.48  |  870.7  |  201.51     |  1251.8      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  14 | 101.22  |  873.9  |  202.69     |  1253.0      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  13 | 101.90  |  877.0  |  203.83     |  1254.0      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  12 | 102.50  |  880.2  |  204.91     |  1255.0      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  11 | 103.00  |  883.4  |  205.88     |  1255.8      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|  10 | 103.43  |  886.5  |  206.72     |  1256.6      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   9 | 103.78  |  889.7  |  207.44     |  1257.2      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   8 | 104.07  |  892.9  |  208.05     |  1257.7      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   7 | 104.31  |  896.0  |  208.57     |  1258.1      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   6 | 104.52  |  899.2  |  209.02     |  1258.5      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   5 | 104.70  |  902.3  |  209.41     |  1258.9      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   4 | 104.86  |  905.5  |  209.76     |  1259.2      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   3 | 105.01  |  908.7  |  210.09     |  1259.5      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   2 | 105.15  |  911.8  |  210.40     |  1259.8      |      --      |     --      |     --      |      --      | 0.500  |    --     |
|   1 | 105.33  |  915.0  |  210.70     |  1049.1      |      --      |     --      |     --      |      --      | 1.000  |3.70110E+06|
+-----+---------+---------+-------------+--------------+--------------+-------------+-------------+--------------+--------+-----------+
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                 MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM          DATE :18-MAY-1987  TIME :16:28:52.60
ETHANOL RECOVERY STILL
     BASE CASE SVD STUDY
  +

          STAGE PROFILES  -- MATERIAL BALANCE

+-----+---------------+---------------+------------------+------------------+------------------+------------------+------------------+
|Stage|  Temperature  |   Pressure    |    Vapor Rate    |   Liquid Rate    |    Feed Rate     |   Liquid Side    |    Vapor Rate    |
| No. |    Deg. C     |     Torr      |     Moles/hr     |     Moles/hr     |     Moles/hr     |     Moles/hr     |     Moles/hr     |
+-----+---------------+---------------+------------------+------------------+------------------+------------------+------------------+
| 50  |     78.13     |    760.00     |      176.43      |      160.58      |        --        |        --        |        --        |
| 49  |     78.24     |    763.16     |      181.58      |      160.59      |        --        |        --        |        --        |
| 48  |     78.35     |    766.33     |      181.59      |      160.59      |        --        |        --        |        --        |
| 47  |     78.45     |    769.49     |      181.59      |      160.59      |        --        |        --        |        --        |
| 46  |     78.56     |    772.65     |      181.59      |      160.58      |        --        |        --        |        --        |
| 45  |     78.66     |    775.82     |      181.58      |      160.58      |        --        |        --        |        --        |
| 44  |     78.77     |    778.98     |      181.58      |      160.57      |        --        |        --        |        --        |
| 43  |     78.88     |    782.14     |      181.57      |      160.56      |        --        |        --        |        --        |
| 42  |     78.98     |    785.31     |      181.56      |      160.54      |        --        |        --        |        --        |
| 41  |     79.09     |    788.47     |      181.54      |      160.52      |        --        |        --        |        --        |
| 40  |     79.20     |    791.63     |      181.52      |      160.49      |        --        |        --        |        --        |
| 39  |     79.31     |    794.80     |      181.49      |      160.46      |        --        |        --        |        --        |
| 38  |     79.42     |    797.96     |      181.46      |      160.43      |        --        |        --        |        --        |
| 37  |     79.53     |    801.12     |      181.43      |      160.38      |        --        |        --        |        --        |
| 36  |     79.64     |    804.29     |      181.38      |      160.33      |        --        |        --        |        --        |
| 35  |     79.76     |    807.45     |      181.33      |      160.27      |        --        |        --        |        --        |
| 34  |     79.87     |    810.61     |      181.27      |      160.19      |        --        |        --        |        --        |
| 33  |     79.99     |    813.78     |      181.19      |      160.11      |        --        |        --        |        --        |
| 32  |     80.12     |    816.94     |      181.11      |      160.00      |        --        |        --        |        --        |
| 31  |     80.25     |    820.10     |      181.00      |      159.87      |        --        |        --        |        --        |
| 30  |     80.40     |    823.27     |      180.87      |      159.72      |        --        |        --        |        --        |
| 29  |     80.55     |    826.43     |      180.72      |      159.54      |        --        |        --        |        --        |
| 28  |     80.73     |    829.59     |      180.54      |      159.31      |        --        |        --        |        --        |
| 27  |     80.93     |    832.76     |      180.31      |      159.03      |        --        |        --        |        --        |
| 26  |     81.17     |    835.92     |      180.03      |      158.67      |        --        |        --        |        --        |
| 25  |     81.48     |    839.08     |      179.67      |      158.21      |        --        |        --        |        --        |
| 24  |     81.88     |    842.24     |      179.21      |      157.62      |        --        |        --        |        --        |
| 23  |     82.43     |    845.41     |      178.62      |      156.83      |        --        |        --        |        --        |
| 22  |     83.24     |    848.57     |      177.83      |      155.77      |        --        |        --        |        --        |
| 21  |     84.48     |    851.73     |      176.77      |      154.36      |        --        |        --        |        --        |
| 20  |     86.51     |    854.90     |      175.36      |      152.57      |        --        |        --        |        --        |
| 19  |     90.01     |    858.06     |      173.57      |      150.99      |        --        |        --        |        --        |
| 18  |     94.92     |    861.22     |      171.99      |      148.31      |        --        |      2.5000      |        --        |
| 17  |     98.58     |    864.39     |      171.81      |      148.85      |        --        |        --        |        --        |
| 16  |     99.70     |    867.55     |      172.35      |      1250.6      |      1072.6      |        --        |        --        |
| 15  |    100.48     |    870.71     |      201.51      |      1251.8      |        --        |        --        |        --        |
| 14  |    101.22     |    873.88     |      202.69      |      1253.0      |        --        |        --        |        --        |
| 13  |    101.90     |    877.04     |      203.83      |      1254.0      |        --        |        --        |        --        |
| 12  |    102.50     |    880.20     |      204.91      |      1255.0      |        --        |        --        |        --        |
| 11  |    103.00     |    883.37     |      205.88      |      1255.8      |        --        |        --        |        --        |
| 10  |    103.43     |    886.53     |      206.72      |      1256.6      |        --        |        --        |        --        |
|  9  |    103.78     |    889.69     |      207.44      |      1257.2      |        --        |        --        |        --        |
|  8  |    104.07     |    892.86     |      208.05      |      1257.7      |        --        |        --        |        --        |
|  7  |    104.31     |    896.02     |      208.57      |      1258.1      |        --        |        --        |        --        |
|  6  |    104.52     |    899.18     |      209.02      |      1258.5      |        --        |        --        |        --        |
|  5  |    104.70     |    902.35     |      209.41      |      1258.9      |        --        |        --        |        --        |
|  4  |    104.86     |    905.51     |      209.76      |      1259.2      |        --        |        --        |        --        |
|  3  |    105.01     |    908.67     |      210.09      |      1259.5      |        --        |        --        |        --        |
|  2  |    105.15     |    911.84     |      210.40      |      1259.8      |        --        |        --        |        --        |
|  1  |    105.33     |    915.00     |      210.70      |      1049.1      |        --        |        --        |        --        |
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                  MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM          DATE :18-MAY-1987  TIME :16:28:52.60
ETHANOL RECOVERY STILL
     BASE CASE SVD STUDY
  +

       STAGE PROFILES  -- ENERGY BALANCE

+------+---------------+---------------+------------------+------------------+------------------+-----------------+
|Stage|  Temperature  |   Pressure    |       Feed       |      Vapor       |      Liquid      |   Heat Added    |
| No. |    Deg. C     |     Torr      |      Btu/hr      |      Btu/hr      |      Btu/hr      |    Btu/hr       |
+------+---------------+---------------+------------------+------------------+------------------+-----------------+
|  50  |     78.13     |    760.00     |        --        |      20418.      |      3753.2      |       --        |
|  49  |     78.24     |    763.16     |        --        |      20420.      |      3756.3      |       --        |
|  48  |     78.35     |    766.33     |        --        |      20423.      |      3759.1      |       --        |
|  47  |     78.45     |    769.49     |        --        |      20425.      |      3761.8      |       --        |
|  46  |     78.56     |    772.65     |        --        |      20427.      |      3764.2      |       --        |
|  45  |     78.66     |    775.82     |        --        |      20430.      |      3766.3      |       --        |
|  44  |     78.77     |    778.98     |        --        |      20432.      |      3768.2      |       --        |
|  43  |     78.88     |    782.14     |        --        |      20435.      |      3769.7      |       --        |
|  42  |     78.98     |    785.31     |        --        |      20437.      |      3770.9      |       --        |
|  41  |     79.09     |    788.47     |        --        |      20440.      |      3771.6      |       --        |
|  40  |     79.20     |    791.63     |        --        |      20442.      |      3771.9      |       --        |
|  39  |     79.31     |    794.80     |        --        |      20445.      |      3771.6      |       --        |
|  38  |     79.42     |    797.96     |        --        |      20448.      |      3770.8      |       --        |
|  37  |     79.53     |    801.12     |        --        |      20450.      |      3769.3      |       --        |
|  36  |     79.64     |    804.29     |        --        |      20453.      |      3766.9      |       --        |
|  35  |     79.76     |    807.45     |        --        |      20456.      |      3763.7      |       --        |
|  34  |     79.87     |    810.61     |        --        |      20459.      |      3759.4      |       --        |
|  33  |     79.99     |    813.78     |        --        |      20462.      |      3753.9      |       --        |
|  32  |     80.12     |    816.94     |        --        |      20465.      |      3746.8      |       --        |
|  31  |     80.25     |    820.10     |        --        |      20468.      |      3738.1      |       --        |
|  30  |     80.40     |    823.27     |        --        |      20472.      |      3727.2      |       --        |
|  29  |     80.55     |    826.43     |        --        |      20477.      |      3713.8      |       --        |
|  28  |     80.73     |    829.59     |        --        |      20482.      |      3697.5      |       --        |
|  27  |     80.93     |    832.76     |        --        |      20489.      |      3677.7      |       --        |
|  26  |     81.17     |    835.92     |        --        |      20498.      |      3653.6      |       --        |
|  25  |     81.48     |    839.08     |        --        |      20510.      |      3624.5      |       --        |
|  24  |     81.88     |    842.24     |        --        |      20527.      |      3589.4      |       --        |
|  23  |     82.43     |    845.41     |        --        |      20553.      |      3547.0      |       --        |
|  22  |     83.24     |    848.57     |        --        |      20590.      |      3495.0      |       --        |
|  21  |     84.48     |    851.73     |        --        |      20646.      |      3430.4      |       --        |
|  20  |     86.51     |    854.90     |        --        |      20728.      |      3351.5      |       --        |
|  19  |     90.01     |    858.06     |        --        |      20837.      |      3278.3      |       --        |
|  18  |     94.92     |    861.22     |        --        |      20933.      |      3262.5      |       --        |
|  17  |     98.58     |    864.39     |        --        |      20938.      |      3273.6      |       --        |
|  16  |     99.70     |    867.55     |      2767.1      |      20892.      |      3253.0      |       --        |
|  15  |    100.48     |    870.71     |        --        |      20910.      |      3272.4      |       --        |
|  14  |    101.22     |    873.88     |        --        |      20928.      |      3291.1      |       --        |
|  13  |    101.90     |    877.04     |        --        |      20944.      |      3308.5      |       --        |
|  12  |    102.50     |    880.20     |        --        |      20957.      |      3323.8      |       --        |
|  11  |    103.00     |    883.37     |        --        |      20968.      |      3337.0      |       --        |
|  10  |    103.43     |    886.53     |        --        |      20976.      |      3348.1      |       --        |
|   9  |    103.78     |    889.69     |        --        |      20982.      |      3357.2      |       --        |
|   8  |    104.07     |    892.86     |        --        |      20985.      |      3364.7      |       --        |
|   7  |    104.31     |    896.02     |        --        |      20987.      |      3370.9      |       --        |
|   6  |    104.52     |    899.18     |        --        |      20986.      |      3376.0      |       --        |
|   5  |    104.70     |    902.35     |        --        |      20984.      |      3380.3      |       --        |
|   4  |    104.86     |    905.51     |        --        |      20980.      |      3383.9      |       --        |
|   3  |    105.01     |    908.67     |        --        |      20974.      |      3386.9      |       --        |
|   2  |    105.15     |    911.84     |        --        |      20966.      |      3389.4      |       --        |

|   1  |    105.33     |    915.00     |        --        |      20956.      |      3389.2      |   3.70110E+06   |
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                    MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM          DATE :18-MAY-1987  TIME :16:28:52.60
ETHANOL RECOVERY STILL
      BASE CASE SVD STUDY
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         STAGE PROFILES FOR COMPONENT NO.   1  ETHANOL

+------+--------------+------------+--------------+--------------+--------------+--------------+------------+
| Stage|______________Mole Fractions_____________ |   K Value    |   Activity   |   Fugacity   |    Stage   |
| No.  |     Feed     |   Liquid   |    Vapor     |              |  Coefficient |  Coefficient | Efficiency |
+------+--------------+------------+--------------+--------------+--------------+--------------+------------+
|  50  |      --      | 0.85793    | 0.85982      |    1.0041    |    1.0169    |   0.99980    |   0.5000   |
|  49  |      --      | 0.85593    | 0.85815      |    1.0047    |    1.0174    |   0.99980    |   0.5000   |
|  48  |      --      | 0.85379    | 0.85638      |    1.0052    |    1.0179    |   0.99980    |   0.5000   |
|  47  |      --      | 0.85152    | 0.85449      |    1.0059    |    1.0184    |   0.99981    |   0.5000   |
|  46  |      --      | 0.84909    | 0.85248      |    1.0065    |    1.0189    |   0.99981    |   0.5000   |
|  45  |      --      | 0.84648    | 0.85033      |    1.0073    |    1.0196    |   0.99981    |   0.5000   |
|  44  |      --      | 0.84368    | 0.84802      |    1.0081    |    1.0203    |   0.99981    |   0.5000   |
|  43  |      --      | 0.84065    | 0.84554      |    1.0090    |    1.0210    |   0.99982    |   0.5000   |
|  42  |      --      | 0.83738    | 0.84287      |    1.0100    |    1.0218    |   0.99982    |   0.5000   |
|  41  |      --      | 0.83383    | 0.83998      |    1.0111    |    1.0228    |   0.99983    |   0.5000   |
|  40  |      --      | 0.82995    | 0.83683      |    1.0124    |    1.0238    |   0.99983    |   0.5000   |
|  39  |      --      | 0.82571    | 0.83341      |    1.0139    |    1.0250    |   0.99984    |   0.5000   |
|  38  |      --      | 0.82104    | 0.82966      |    1.0155    |    1.0263    |   0.99985    |   0.5000   |
|  37  |      --      | 0.81589    | 0.82553      |    1.0174    |    1.0278    |   0.99985    |   0.5000   |
|  36  |      --      | 0.81015    | 0.82097      |    1.0196    |    1.0296    |   0.99987    |   0.5000   |
|  35  |      --      | 0.80373    | 0.81590      |    1.0222    |    1.0316    |   0.99988    |   0.5000   |
|  34  |      --      | 0.79650    | 0.81023      |    1.0253    |    1.0340    |   0.99990    |   0.5000   |
|  33  |      --      | 0.78830    | 0.80384      |    1.0289    |    1.0368    |   0.99991    |   0.5000   |
|  32  |      --      | 0.77891    | 0.79659      |    1.0334    |    1.0402    |   0.99994    |   0.5000   |
|  31  |      --      | 0.76805    | 0.78830      |    1.0388    |    1.0443    |   0.99997    |   0.5000   |
|  30  |      --      | 0.75538    | 0.77871      |    1.0457    |    1.0495    |    1.0000    |   0.5000   |
|  29  |      --      | 0.74039    | 0.76751      |    1.0545    |    1.0560    |    1.0001    |   0.5000   |
|  28  |      --      | 0.72244    | 0.75429      |    1.0660    |    1.0644    |    1.0001    |   0.5000   |
|  27  |      --      | 0.70062    | 0.73844      |    1.0815    |    1.0755    |    1.0002    |   0.5000   |
|  26  |      --      | 0.67364    | 0.71919      |    1.1029    |    1.0908    |    1.0003    |   0.5000   |
|  25  |      --      | 0.63971    | 0.69540      |    1.1338    |    1.1125    |    1.0005    |   0.5000   |
|  24  |      --      | 0.59626    | 0.66550      |    1.1803    |    1.1448    |    1.0008    |   0.5000   |
|  23  |      --      | 0.53966    | 0.62724      |    1.2545    |    1.1959    |    1.0012    |   0.5000   |
|  22  |      --      | 0.46509    | 0.57747      |    1.3824    |    1.2830    |    1.0018    |   0.5000   |
|  21  |      --      | 0.36732    | 0.51198      |    1.6271    |    1.4470    |    1.0028    |   0.5000   |
|  20  |      --      | 0.24598    | 0.42630      |    2.1642    |    1.7921    |    1.0045    |   0.5000   |
|  19  |      --      | 0.12357    | 0.32025      |    3.4558    |    2.5293    |    1.0077    |   0.5000   |
|  18  |      --      | 4.79806E-02| 0.21347      |    5.8299    |    3.6007    |    1.0126    |   0.5000   |
|  17  |      --      | 2.13701E-02| 0.14721      |    7.9787    |    4.3632    |    1.0165    |   0.5000   |
|  16  |  1.70000E-02 | 1.64737E-02| 0.12392      |    8.8557    |    4.6796    |    1.0177    |   0.5000   |
|  15  |      --      | 1.32586E-02| 0.10195      |    9.2243    |    4.7662    |    1.0186    |   0.5000   |
|  14  |      --      | 1.03967E-02| 8.15978E-02  |    9.5776    |    4.8452    |    1.0194    |   0.5000   |
|  13  |      --      | 7.96120E-03| 6.36210E-02  |    9.8986    |    4.9139    |    1.0201    |   0.5000   |
|  12  |      --      | 5.97077E-03| 4.84369E-02  |    10.176    |    4.9709    |    1.0208    |   0.5000   |
|  11  |      --      | 4.39952E-03| 3.61133E-02  |    10.406    |    5.0167    |    1.0214    |   0.5000   |
|  10  |      --      | 3.19409E-03| 2.64448E-02  |    10.589    |    5.0523    |    1.0218    |   0.5000   |
|   9  |      --      | 2.29005E-03| 1.90663E-02  |    10.732    |    5.0796    |    1.0222    |   0.5000   |
|   8  |      --      | 1.62384E-03| 1.35568E-02  |    10.840    |    5.1003    |    1.0225    |   0.5000   |
|   7  |      --      | 1.13941E-03| 9.51150E-03  |    10.922    |    5.1161    |    1.0228    |   0.5000   |
|   6  |      --      | 7.90667E-04| 6.57865E-03  |    10.984    |    5.1286    |    1.0230    |   0.5000   |
|   5  |      --      | 5.41490E-04| 4.47250E-03  |    11.033    |    5.1389    |    1.0231    |   0.5000   |
|   4  |      --      | 3.64473E-04| 2.97084E-03  |    11.073    |    5.1480    |    1.0233    |   0.5000   |
|   3  |      --      | 2.39286E-04| 1.90606E-03  |    11.107    |    5.1568    |    1.0234    |   0.5000   |
|   2  |      --      | 1.51087E-04| 1.15437E-03  |    11.139    |    5.1658    |    1.0235    |   0.5000   |

|   1  |      --      | 5.57672E-05| 6.25719E-04  |    11.220    |    5.1917    |    1.0237    |   1.0000   |
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                   MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM           DATE :18-MAY-1987  TIME :16:28:52.60
ETHANOL RECOVERY STILL
      BASE CASE SVD STUDY
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       STAGE PROFILES FOR COMPONENT NO.   2  WATER

+------+-------------+-------------+-------------+-------------+-------------+-------------+-------------+
| Stage|_____________Mole Fractions______________|   K Value   |  Activity   |  Fugacity   |    Stage    |
| No.  |     Feed    |    Liquid   |    Vapor    |             | Coefficient | Coefficient | Efficiency  |
+------+-------------+-------------+-------------+-------------+-------------+-------------+-------------+
|  50  |      --     |   0.14207   |   0.14018   |   0.97495   |   2.2571    |   0.99598   |   0.5000    |
|  49  |      --     |   0.14407   |   0.14185   |   0.97226   |   2.2504    |   0.99597   |   0.5000    |
|  48  |      --     |   0.14621   |   0.14362   |   0.96942   |   2.2432    |   0.99595   |   0.5000    |
|  47  |      --     |   0.14848   |   0.14551   |   0.96643   |   2.2357    |   0.99593   |   0.5000    |
|  46  |      --     |   0.15091   |   0.14752   |   0.96326   |   2.2278    |   0.99591   |   0.5000    |
|  45  |      --     |   0.15352   |   0.14967   |   0.95990   |   2.2194    |   0.99590   |   0.5000    |
|  44  |      --     |   0.15632   |   0.15198   |   0.95633   |   2.2105    |   0.99588   |   0.5000    |
|  43  |      --     |   0.15935   |   0.15446   |   0.95253   |   2.2010    |   0.99586   |   0.5000    |
|  42  |      --     |   0.16262   |   0.15713   |   0.94846   |   2.1908    |   0.99584   |   0.5000    |
|  41  |      --     |   0.16617   |   0.16002   |   0.94409   |   2.1799    |   0.99582   |   0.5000    |
|  40  |      --     |   0.17005   |   0.16317   |   0.93939   |   2.1682    |   0.99580   |   0.5000    |
|  39  |      --     |   0.17429   |   0.16659   |   0.93433   |   2.1555    |   0.99578   |   0.5000    |
|  38  |      --     |   0.17895   |   0.17034   |   0.92883   |   2.1417    |   0.99576   |   0.5000    |
|  37  |      --     |   0.18411   |   0.17446   |   0.92285   |   2.1267    |   0.99574   |   0.5000    |
|  36  |      --     |   0.18984   |   0.17902   |   0.91633   |   2.1103    |   0.99571   |   0.5000    |
|  35  |      --     |   0.19625   |   0.18409   |   0.90916   |   2.0923    |   0.99569   |   0.5000    |
|  34  |      --     |   0.20347   |   0.18976   |   0.90126   |   2.0723    |   0.99567   |   0.5000    |
|  33  |      --     |   0.21165   |   0.19613   |   0.89250   |   2.0500    |   0.99564   |   0.5000    |
|  32  |      --     |   0.22101   |   0.20337   |   0.88275   |   2.0251    |   0.99561   |   0.5000    |
|  31  |      --     |   0.23181   |   0.21163   |   0.87182   |   1.9969    |   0.99559   |   0.5000    |
|  30  |      --     |   0.24439   |   0.22117   |   0.85952   |   1.9649    |   0.99556   |   0.5000    |
|  29  |      --     |   0.25922   |   0.23228   |   0.84559   |   1.9283    |   0.99553   |   0.5000    |
|  28  |      --     |   0.27691   |   0.24537   |   0.82974   |   1.8860    |   0.99550   |   0.5000    |
|  27  |      --     |   0.29830   |   0.26098   |   0.81163   |   1.8368    |   0.99547   |   0.5000    |
|  26  |      --     |   0.32457   |   0.27986   |   0.79089   |   1.7792    |   0.99544   |   0.5000    |
|  25  |      --     |   0.35735   |   0.30302   |   0.76713   |   1.7111    |   0.99542   |   0.5000    |
|  24  |      --     |   0.39898   |   0.33190   |   0.74001   |   1.6304    |   0.99541   |   0.5000    |
|  23  |      --     |   0.45277   |   0.36855   |   0.70950   |   1.5346    |   0.99542   |   0.5000    |
|  22  |      --     |   0.52328   |   0.41586   |   0.67640   |   1.4222    |   0.99547   |   0.5000    |
|  21  |      --     |   0.61586   |   0.47777   |   0.64407   |   1.2945    |   0.99560   |   0.5000    |
|  20  |      --     |   0.73250   |   0.55889   |   0.62381   |   1.1629    |   0.99590   |   0.5000    |
|  19  |      --     |   0.85533   |   0.66084   |   0.64731   |   1.0594    |   0.99656   |   0.5000    |
|  18  |      --     |   0.93804   |   0.76801   |   0.74143   |   1.0145    |   0.99765   |   0.5000    |
|  17  |      --     |   0.97165   |   0.84052   |   0.83486   |   1.0044    |   0.99854   |   0.5000    |
|  16  |   0.98200   |   0.98160   |   0.86985   |   0.86433   |   1.0026    |   0.99880   |   0.5000    |
|  15  |      --     |   0.98473   |   0.89127   |   0.88493   |   1.0022    |   0.99898   |   0.5000    |
|  14  |      --     |   0.98752   |   0.91112   |   0.90486   |   1.0020    |   0.99915   |   0.5000    |
|  13  |      --     |   0.98990   |   0.92867   |   0.92314   |   1.0018    |   0.99931   |   0.5000    |
|  12  |      --     |   0.99185   |   0.94352   |   0.93907   |   1.0016    |   0.99945   |   0.5000    |
|  11  |      --     |   0.99340   |   0.95563   |   0.95235   |   1.0015    |   0.99957   |   0.5000    |
|  10  |      --     |   0.99460   |   0.96519   |   0.96301   |   1.0015    |   0.99966   |   0.5000    |
|   9  |      --     |   0.99552   |   0.97257   |   0.97130   |   1.0014    |   0.99973   |   0.5000    |
|   8  |      --     |   0.99622   |   0.97819   |   0.97763   |   1.0014    |   0.99979   |   0.5000    |
|   7  |      --     |   0.99676   |   0.98246   |   0.98238   |   1.0014    |   0.99983   |   0.5000    |
|   6  |      --     |   0.99718   |   0.98572   |   0.98595   |   1.0014    |   0.99986   |   0.5000    |
|   5  |      --     |   0.99752   |   0.98826   |   0.98865   |   1.0014    |   0.99989   |   0.5000    |
|   4  |      --     |   0.99781   |   0.99033   |   0.99073   |   1.0014    |   0.99991   |   0.5000    |
|   3  |      --     |   0.99808   |   0.99210   |   0.99239   |   1.0013    |   0.99992   |   0.5000    |
|   2  |      --     |   0.99834   |   0.99371   |   0.99379   |   1.0013    |   0.99993   |   0.5000    |
|   1  |      --     |   0.99896   |   0.99529   |   0.99633   |   1.0013    |   0.99995   |   1.0000    |
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                    MULTICOMPONENT,MULTISTAGE DISTILLATION PROGRAM          DATE : 18-MAY-1987  TIME : 16:28:52.60
ETHANOL RECOVERY STILL
      BASE CASE SVD STUDY
   +

        STAGE PROFILES FOR COMPONENT NO.   3  FUSELS

+------+-------------+-------------+--------------+-------------+-------------+--------------+-----------+
| Stage|_____________Mole Fractions______________ |   K Value   |  Activity   |  Fugacity    |   Stage   |
| No.  |    Feed     |   Liquid    |    Vapor   . |             | Coefficient | Coefficient  | Efficiency|
+------+-------------+-------------+--------------+-------------+-------------+--------------+-----------+
|  50  |     --      | 4.65620E-09 | 2.53742E-09  | 0.14254     |   1.2145    | 0.97021      |  0.5000   |
|  49  |     --      | 8.30196E-09 | 4.41117E-09  | 0.14298     |   1.2168    | 0.97013      |  0.5000   |
|  48  |     --      | 1.45721E-08 | 7.63531E-09  | 0.14344     |   1.2193    | 0.97004      |  0.5000   |
|  47  |     --      | 2.53502E-08 | 1.31803E-08  | 0.14393     |   1.2219    | 0.96995      |  0.5000   |
|  46  |     --      | 4.38673E-08 | 2.27120E-08  | 0.14444     |   1.2247    | 0.96987      |  0.5000   |
|  45  |     --      | 7.56621E-08 | 3.90876E-08  | 0.14499     |   1.2278    | 0.96979      |  0.5000   |
|  44  |     --      | 1.30222E-07 | 6.72050E-08  | 0.14556     |   1.2311    | 0.96971      |  0.5000   |
|  43  |     --      | 2.23787E-07 | 1.15454E-07  | 0.14618     |   1.2347    | 0.96963      |  0.5000   |
|  42  |     --      | 3.84128E-07 | 1.98196E-07  | 0.14684     |   1.2386    | 0.96955      |  0.5000   |
|  41  |     --      | 6.58697E-07 | 3.39987E-07  | 0.14755     |   1.2429    | 0.96947      |  0.5000   |
|  40  |     --      | 1.12848E-06 | 5.82785E-07  | 0.14831     |   1.2477    | 0.96940      |  0.5000   |
|  39  |     --      | 1.93154E-06 | 9.98200E-07  | 0.14915     |   1.2529    | 0.96932      |  0.5000   |
|  38  |     --      | 3.30297E-06 | 1.70831E-06  | 0.15007     |   1.2588    | 0.96925      |  0.5000   |
|  37  |     --      | 5.64240E-06 | 2.92095E-06  | 0.15108     |   1.2653    | 0.96919      |  0.5000   |
|  36  |     --      | 9.62812E-06 | 4.98943E-06  | 0.15221     |   1.2727    | 0.96912      |  0.5000   |
|  35  |     --      | 1.64090E-05 | 8.51337E-06  | 0.15348     |   1.2811    | 0.96907      |  0.5000   |
|  34  |     --      | 2.79267E-05 | 1.45083E-05  | 0.15492     |   1.2906    | 0.96901      |  0.5000   |
|  33  |     --      | 4.74532E-05 | 2.46904E-05  | 0.15657     |   1.3017    | 0.96897      |  0.5000   |
|  32  |     --      | 8.04841E-05 | 4.19511E-05  | 0.15849     |   1.3146    | 0.96893      |  0.5000   |
|  31  |     --      | 1.36211E-04 | 7.11465E-05  | 0.16075     |   1.3299    | 0.96890      |  0.5000   |
|  30  |     --      | 2.29924E-04 | 1.20397E-04  | 0.16347     |   1.3482    | 0.96888      |  0.5000   |
|  29  |     --      | 3.86886E-04 | 2.03207E-04  | 0.16679     |   1.3705    | 0.96888      |  0.5000   |
|  28  |     --      | 6.48437E-04 | 3.41884E-04  | 0.17095     |   1.3981    | 0.96890      |  0.5000   |
|  27  |     --      | 1.08134E-03 | 5.72916E-04  | 0.17629     |   1.4333    | 0.96895      |  0.5000   |
|  26  |     --      | 1.79128E-03 | 9.55200E-04  | 0.18338     |   1.4792    | 0.96904      |  0.5000   |
|  25  |     --      | 2.94041E-03 | 1.58192E-03  | 0.19316     |   1.5413    | 0.96919      |  0.5000   |
|  24  |     --      | 4.76398E-03 | 2.59586E-03  | 0.20735     |   1.6293    | 0.96941      |  0.5000   |
|  23  |     --      | 7.56612E-03 | 4.20388E-03  | 0.22933     |   1.7618    | 0.96976      |  0.5000   |
|  22  |     --      | 1.16281E-02 | 6.67262E-03  | 0.26647     |   1.9782    | 0.97029      |  0.5000   |
|  21  |     --      | 1.68292E-02 | 1.02467E-02  | 0.33748     |   2.3734    | 0.97110      |  0.5000   |
|  20  |     --      | 2.15168E-02 | 1.48138E-02  | 0.49794     |   3.2014    | 0.97243      |  0.5000   |
|  19  |     --      | 2.11034E-02 | 1.89135E-02  | 0.91456     |   5.0398    | 0.97467      |  0.5000   |
|  18  |     --      | 1.39780E-02 | 1.85266E-02  |  1.7731     |   7.9138    | 0.97782      |  0.5000   |
|  17  |     --      | 6.98283E-03 | 1.22695E-02  |  2.6215     |   10.064    | 0.98026      |  0.5000   |
|  16  | 1.00000E-03 | 1.92278E-03 | 6.23347E-03  |  2.9557     |   10.870    | 0.98106      |  0.5000   |
|  15  |     --      | 2.00877E-03 | 6.78381E-03  |  3.1267     |   11.177    | 0.98154      |  0.5000   |
|  14  |     --      | 2.08291E-03 | 7.28675E-03  |  3.2938     |   11.464    | 0.98200      |  0.5000   |
|  13  |     --      | 2.14134E-03 | 7.71279E-03  |  3.4486     |   11.718    | 0.98241      |  0.5000   |
|  12  |     --      | 2.18179E-03 | 8.04086E-03  |  3.5851     |   11.933    | 0.98275      |  0.5000   |
|  11  |     --      | 2.20341E-03 | 8.25972E-03  |  3.7003     |   12.110    | 0.98304      |  0.5000   |
|  10  |     --      | 2.20625E-03 | 8.36626E-03  |  3.7939     |   12.249    | 0.98325      |  0.5000   |
|   9  |     --      | 2.19071E-03 | 8.36211E-03  |  3.8682     |   12.358    | 0.98341      |  0.5000   |
|   8  |     --      | 2.15698E-03 | 8.25010E-03  |  3.9261     |   12.441    | 0.98353      |  0.5000   |
|   7  |     --      | 2.10478E-03 | 8.03161E-03  |  3.9711     |   12.506    | 0.98361      |  0.5000   |
|   6  |     --      | 2.03317E-03 | 7.70484E-03  |  4.0064     |   12.556    | 0.98366      |  0.5000   |
|   5  |     --      | 1.94048E-03 | 7.26399E-03  |  4.0346     |   12.597    | 0.98370      |  0.5000   |
|   4  |     --      | 1.82426E-03 | 6.69889E-03  |  4.0580     |   12.632    | 0.98372      |  0.5000   |
|   3  |     --      | 1.68128E-03 | 5.99487E-03  |  4.0784     |   12.663    | 0.98373      |  0.5000   |
|   2  |     --      | 1.50750E-03 | 5.13275E-03  |  4.0973     |   12.694    | 0.98374      |  0.5000   |
|   1  |     --      | 9.89091E-04 | 4.08886E-03  |  4.1340     |   12.762    | 0.98378      |  1.0000   |
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VITA

David Lynn Canter was born in Morristown, Tennessee on October 12, 1961 and attended public school in Loudon, Tennessee. He graduated from Morristown Hamblen High School West in 1979 and entered the University of Tennessee, Knoxville in the fall of that year. He graduated with a Bachelor's degree in chemical engineering in June of 1983. He is a member of Tau Beta Pi, Phi Kappa Phi and the American Institute of Chemical Engineeers.